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Electrification of isolated communities in Mexico: The case of wind energy systems

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Electrification of isolated communities in Mexico: The case of wind energy systems

by

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Abstract

Electrification of isolated communities in Mexico: The case of wind energy systems

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The Mexican government, supported by international organizations, has financed a myriad of rural electrification projects. However, high costs and a lack of trained staff in isolated regions have obstructed the expansion of the grid to all rural areas, particularly in the poorest regions of the country.

This study focuses on rural villages in the State of Chiapas, Mexico, and compares the amount required to connect each isolated town to the national grid to the cost to build an independent system powered by wind energy systems.

It was concluded that, in most cases, the use of a microgrid is the best solution; the application of wind energy systems must be complemented by training in O&M activities for local inhabitants, and by the allocation of financial resources as grants for funding.

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Acronyms and Abbreviations

CDI	Comisión Nacional para el Desarrollo de los Pueblos Indígenas
CE	Centro de Energía de Chile
CFE	Comisión Federal de Electricidad
CONAPO	Consejo Nacional de Población,
CRE	Comisión Reguladora de Energía
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
IDE	Instituto de Desarrollo de Energías del Estado de Chiapas
IEA	International Energy Agency
INEGI	Instituto Nacional de Estadística y Geografía
INERE	Inventario Nacional de Energías Renovables
kW	Kilowatt
kWh	Kilowatt-hour
$kWh/m^2/d$	Kilowatt-hour per meter square per day
MNRE	The Ministry of New and Renewable Energy
MW	Megawatt
MWh	Megawatt-hour
MXN	Mexican peso. Used for reference only.
NEC	Non-electrified rural community
NREL	National Renewable Energy Laboratory
O&M	Operation and maintenance
PV	Photovoltaic
SENER	Secretaría de Energía

USGS	United States Geological Survey
WWEA	World Wind Energy Association
USDeq	Original amount in Mexican pesos converted into United States dollars at the exchange rate as of December 31, 2016, 1 USD =20.6194 MXN.
VBA	Visual Basic for Applications

Chapter 1: Executive Summary

Comisión Federal de Electricidad (CFE), the state-owned electric utility of México, has focused on providing grid-supplied electrical power to all rural towns with more than 100 homes in Mexico. However, there are still a large number of smaller towns that remain outside the scope. The conventional approach of electrification is expensive and faces technical difficulties in locations without infrastructure. Additionally, CFE adds extra burden to the cost by planning according to an overestimated use of electricity.

An alternative solution to a typical grid extension is to create autonomous microgrids powered by wind energy. Technological developments in renewable technologies and in battery storage provide promise of lower costs and smarter infrastructure, especially in the case of wind turbines (EIA, 2016). Investment can be reduced with an independent grid by avoiding idle capacity. A microgrid is also relatively easy to operate, and it has been shown in several attempts that community engagement can be helpful to continue the operation with no significant outside intervention.

The general objective of this thesis is to determine the most cost-effective option to complete the electrification of unconnected communities in the State of Chiapas, Mexico. The optimal cost of electrification is defined as the lowest cost between using a wind energy system in the form of a microgrid and a typical extension of the grid.

Two additional cases are explored: one case in which the government can subsidize a wind-energy company to settle in a specific town, and other where towns form a regional group.

It was concluded that a wind energy system requires a lower investment than building an extension of the grid from the nearest electrified town, and a lower investment than a solar photovoltaic system too. The construction of a successful wind energy system requires full commitment from the government and its sponsorship of financial resources and training for rural inhabitants.

The results and frameworks provided in this thesis might be useful in policy-making to establish an order of electrification of unconnected towns in Mexico.

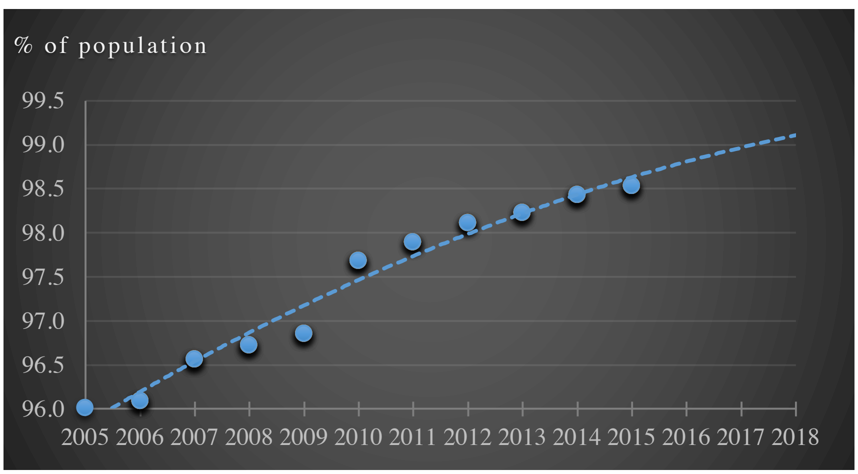
Chapter 2: Introduction

Access to electricity in Mexico

A significant amount of the tasks carried out by a person throughout the day in developed communities are associated with the use of electricity; in particular, productive activities that require an uninterrupted supply of energy. Therefore, access to electricity is widely considered a key element for human development.

The Comisión Federal de Electricidad, widely known as CFE, is the state-owned electric utility in charge of the electrification of households in Mexico. CFE (2015) stated that a coverage of 99% will be reached in 2018; the estimation seems as a feasible goal based on historic data (see Figure 1). The federal government has publicly declared on several occasions its willingness to improve the level of coverage in electrification nationwide. In accordance with the statements, the Mexican government, supported by international organizations, has financed a myriad of rural electrification projects. However, in spite of significant efforts of electrification, high costs and a lack of trained staff in isolated regions have obstructed the expansion of the grid to all rural areas.

Figure 1. Access to electricity in Mexico from 2005 to 2015



Data from: Comisión Federal de Electricidad, September 2016, Indicadores operativos, http://cfe.mx/ConoceCFE/1_AcercadeCFE/Estadisticas/Paginas/Indicadores-operativos.aspx

CFE reported that 1.5% of Mexico's population did not have access to electricity at the end of 2015 (CFE, 2016). The latter implies that there were still more than 1.7 million people without access to the grid throughout the country, mainly in rural areas. Electrification in Mexico was found to be slightly inferior when compared to the average of other Organization for Economic Cooperation Development members with 99.1% and 99.4%, respectively (World Bank, 2017).

Mexico is a country of extreme diversity among its different states, both in its socioeconomic and geographic conditions. The states with the highest number of non-electrified households are (INEGI, 2015): Oaxaca (32,432), Chiapas (28,838), Yucatán (7,390), and Quintana Roo (5,232). Non-electrified communities (NECs) in those locations are difficult to access, they lack fully paved roads and infrastructure, and they are frequently widely dispersed, which is partially due to their geographic situation (see Figure 2).

Figure 2. Physiography of Mexico

Source: The University of Texas Systems, 1975, physiography, https://www.lib.utexas.edu/maps/atlas_mexico/physiography.jpg

An extension of the grid

In Mexico, as in other parts of the world, isolated communities can either use basic resources, such as firewood and candles, or diesel generators for their energy needs. Diesel generators are characterized for having high operating and maintenance costs, and firewood and candles are considered to have a low efficiency. Existing photovoltaics microgrids in rural Mexico benefit locals by substituting the use of candles and petroleum products, and also by extending the hours of domestic activities, self-consumption and academic activities (Acciona, 2016).

In order to provide a more consistent and inexpensive electricity supply, the extension of the grid is an obvious answer; however, experience from other developing countries does not advise a conventional approach. Results obtained by Burlig (2016) demonstrate that an increase in electricity consumption in rural villages in India implied a longer payback period than previously estimated because of high costs and inefficiencies in the supply chain of the national electric grid. The authors also concluded that electricity infrastructure might not necessarily boost economic growth in rural economies, contradicting the widespread idea that electrification is an essential tool to reduce poverty and increase economic and academic progress; the latter could possibly be due to a lack of productive rural activities that could benefit from the changes or due to a high cost of investment. Haas (2016) obtained similar results for Kenya; the conclusions indicated that the benefits of connecting rural towns depended on the organizational and economic performance of political institutions and of the electric utility to provide social welfare. The authors found better results for the microgrid approach.

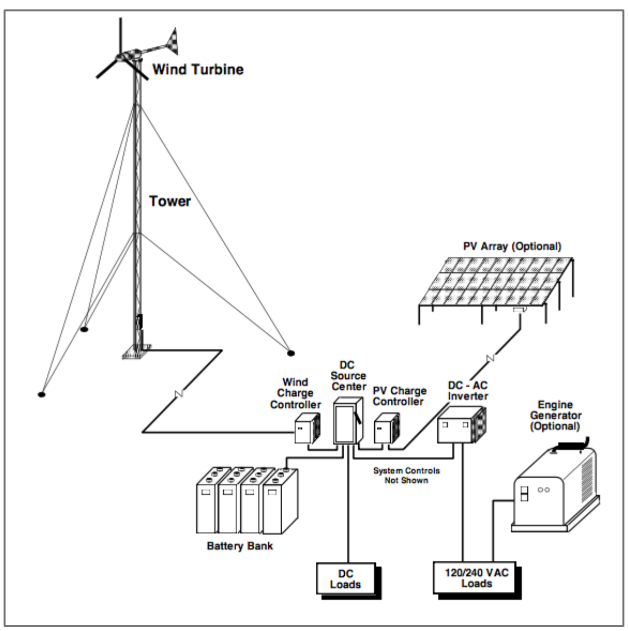
It is important to find and generate electrical-system solutions that are more efficient in technical and economic terms, both to reduce costs and to accelerate the electrification of rural communities. Access to inexpensive electricity has drawn attention in many countries, with a high number un unconnected villages aiming to repeat the successes of electrification programs in developed countries, for example, the Indian government intends to add 500 MW in capacity as microgrids in the following years (MNRE of India, 2016). However, an agreement has not been reached as to how implement it, either by investments in large-scale infrastructure or in small-scale decentralized solutions (Hass, 2016).

An alternative solution to typical projects is to create autonomous microgrids powered by renewable energy for each town.

Microgrids as an alternative

As shown in Figure 3, a "microgrid" is a system with a renewable energy-based electricity generator and a maximum capacity of 10 kW, that supplies electricity to residential consumers through a distribution network (MNRE of India, 2016). This document will limit the definition when a microgrid is mentioned to only the cases in which wind energy is a source due to better results when compared to solar photovoltaics energy generation, as will be explained later.

Figure 3. Diagram of a small microgrid



Source: Bergey Windpower Co., 2014, Small wind turbines for microgrids, http://bergey.com/documents/2014/06/small-wind-turbines-for-microgrids-faq.pdf

Microgrids powered by a renewable energy source have the advantage of a lower carbon footprint and lower production costs; however, they require a relatively high investment and have no reliable availability either. The reliability of the system can be increased by implementing battery energy storage, although that incurs even higher investment (Roje, 2015).

Additionally, an independent grid avoids a significant investment in transmission and distribution capacity. For Mexico, CFE installs distribution lines to serve rural towns, which have the capacity to serve urban towns; more details are shown in chapter 10.

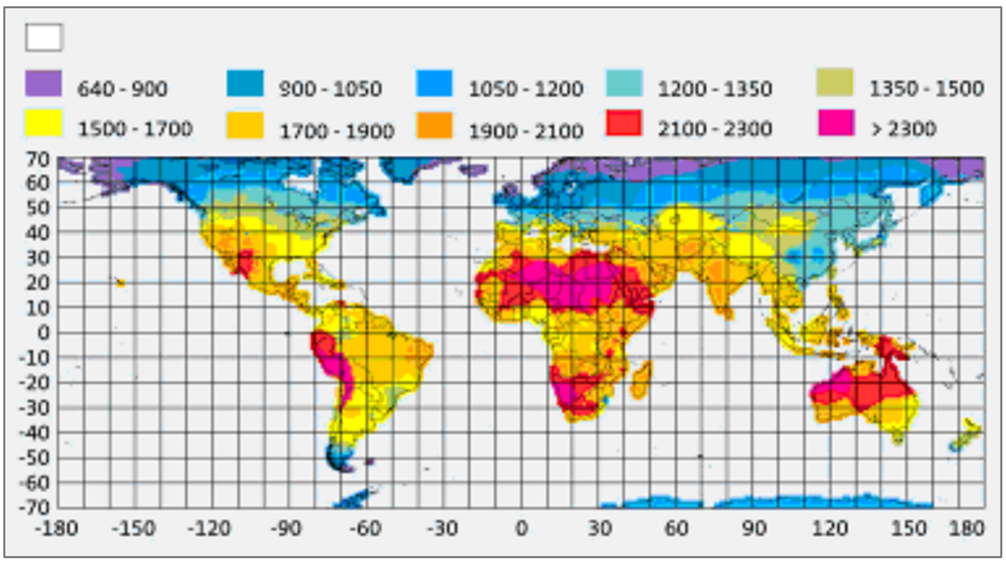
A microgrid is also relatively easy to operate, and it has been shown that community involvement in O&M activities can be very helpful to promote long-term sustainability of power supply systems with no significant or costly outside intervention. Jiménez-Estévez et. al (June 2014) claim that systems with little or no community engagement regularly show technical problems soon after the implementation. The microgrid approach would address the difficulty to transport regularly trained staff for operation and maintenance activities to the communities; however, it is crucial to assess the abilities and interest of the individuals to participate in a program to operate and maintain the equipment, since local population might be opposed to the project (Grunstein, 2016). Unrecorded comments by Chilean researchers indicate that certain parts of the population would rather wait for the grid to reach them eventually instead of having a renewable/alternative system that might obstruct a future development of the grid in that region. Hence, it is important to follow a methodology for the introduction of a smart microgrid system in a rural community to continue a correct operation after installation even in the presence of a lack of local capabilities and proper maintenance procedures (Alvial-Palavicino, 2011).

Some of other advantages of the utilization of this technology include the full use of existing facilities, avoiding the waste of equipment and the network already acquired by the community, an optimal allocation of storage systems, congestion relief, loss reduction, voltage support, mitigation of voltage dips, peak shaving, and an overall improvement of energy efficiency, reliability, and power quality (Ubilla, 2014).

Chapter 3: Renewable energy resources in Mexico and in the State of Chiapas

Until now, there has not been a wide application of renewable technologies in Mexico, even though resources are better or equivalent to those seen in countries with a high deployment of wind and solar generation (See Figure 4). Electricity generation from renewable sources in Mexico is still small compared to the United States, with 3.9% of total generation compared to 13% in America for 2015 (EIA, 2015). Wind electricity generation represents 2.5% in Mexico, whereas in the US it represents 4.5%.

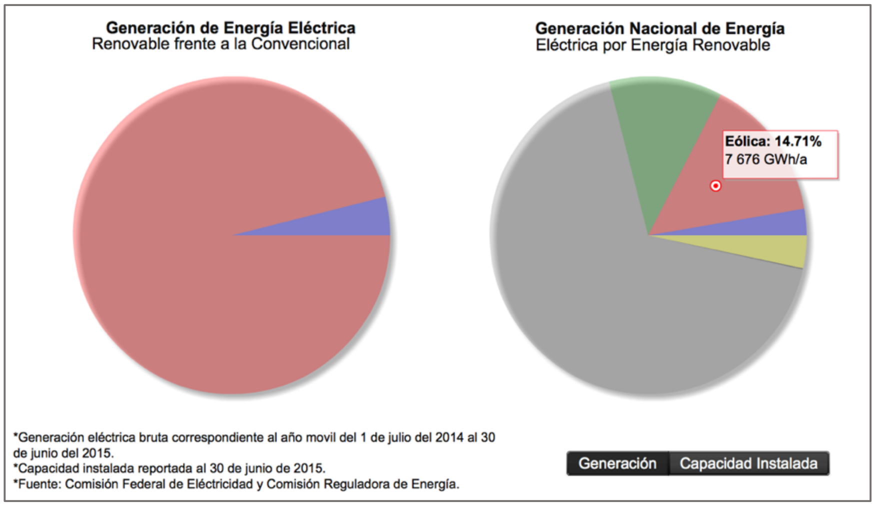
Figure 4. World map of solar radiation



Source: DOF, Programa Especial para el Aprovechamiento de Energías Renovables, http://dof.gob.mx/nota_detalle.php?codigo=5101826&fecha=06/08/2009

Generation in Mexico from wind systems accounts for 14.71% of renewable generation, after hydraulic and geothermal technologies, whereas installed solar systems produce only 0.12%, as can be seen in Figure 5 (INERE, 2016).

Figure 5. Electricity generation: conventional and renewable systems (left), renewable generation by type of energy (right)

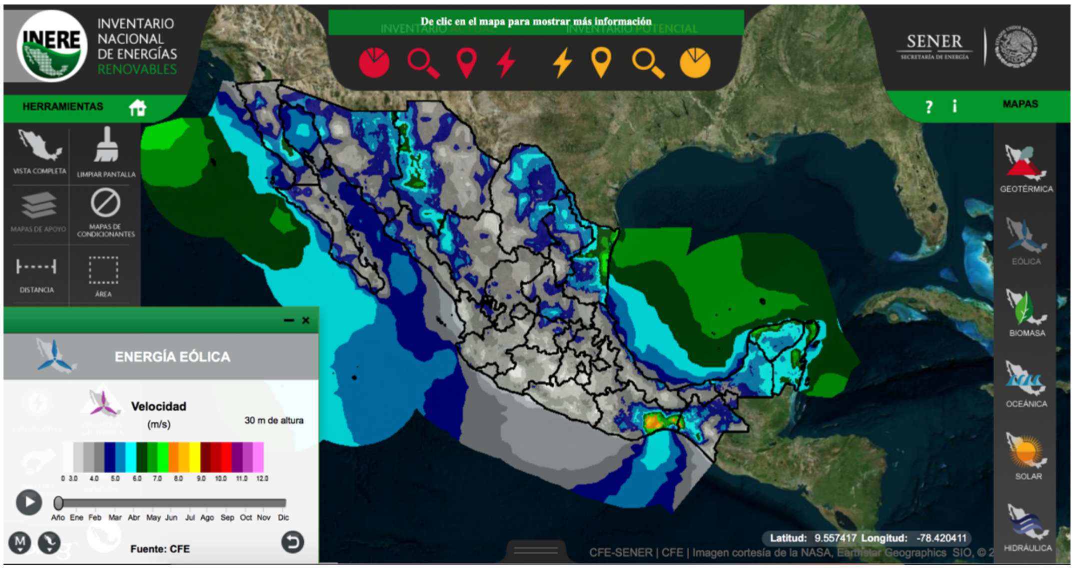


Source: Secretaría de Energía, 2016, Inventario Nacional de Energías Renovables, *https://dgel.energia.gob.mx/inere/*

Wind resources

Mexico possesses rich wind resources in certain sections of the country that can be used to generate electricity. Figure 6 shows wind speeds in Mexico at a height of 30 meters. Some of the advantages of wind power are the following (DOE, 2017): it is a clean fuel source, it is inexhaustible, it can be cost-effective under certain conditions, it can be applied on remote locations, farmers can continue to work their land during operation, and small turbines do not have a significant effect on wildlife. The main environmental concern for rural use is related to the disposal of batteries, which is shared with PV systems (World Bank, 2007).

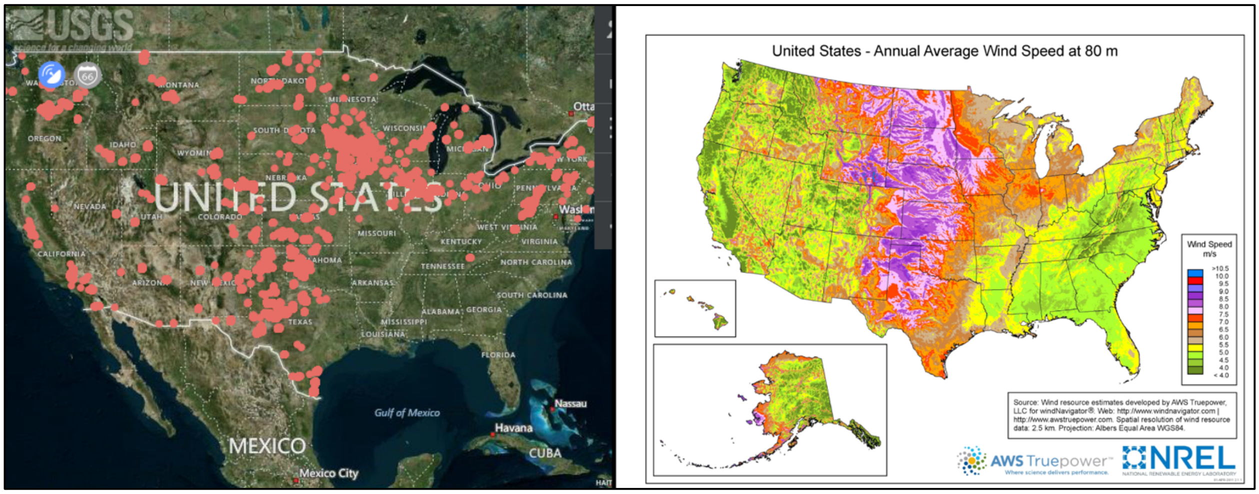
Figure 6. Average wind speed at 30 meters



Source: Secretaría de Energía, 2016, Inventario Nacional de Energías Renovables, *https://dgel.energia.gob.mx/inere/*

As can be seen in the NREL and USGS maps in Figures 7 and 8, there is a close relation between location of wind turbines and wind resources for the United States. Most wind farms are located in places where wind speed is above 5.5 m/s at a height of 30 meters, and above 6.5 m/s at a height of 80 meters. Guzmán-Escoto (2015) evaluated hybrid systems in Mexico and concluded that a wind option was not economically feasible with a speed of less than 4.0 m/s at 30 meters of height. Based on Figure 6, and on the analysis abovementioned, only non-gray areas have a significant potential to host wind turbines. For this reason, gray areas are left out of the present study.

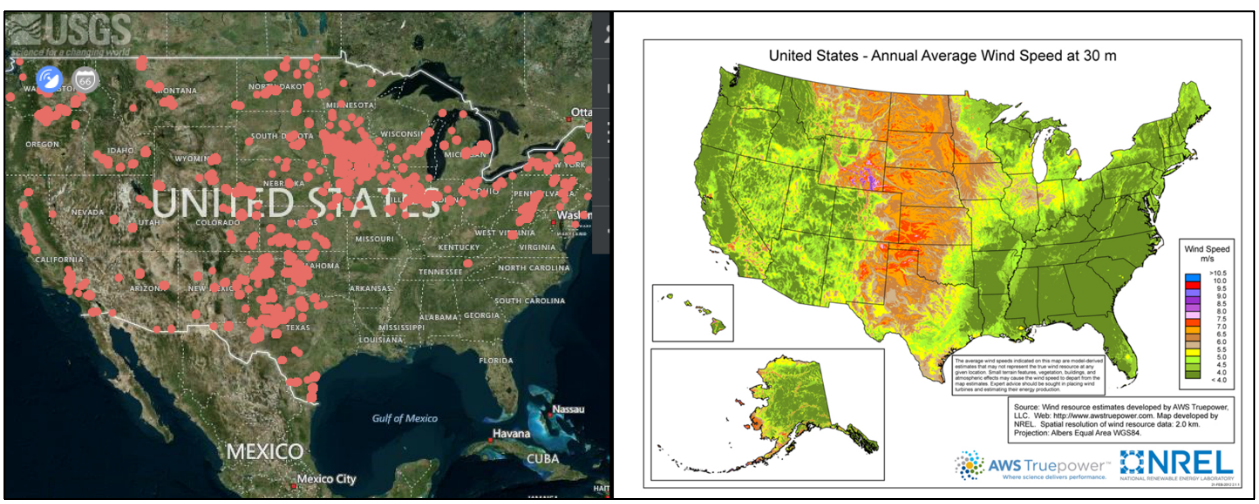
Figure 7. Location of wind turbines (left) and wind speed at 80 meters (right)



Sources: *USGS, <u>http://eerscmap.usgs.gov/windfarm/</u>*

NREL, <u>http://www.nrel.gov/gis/images/80m_wind/USwind300dpe4-11.jpg</u>

Figure 8. Location of wind turbines (left) and wind speed at 30 meters (right)

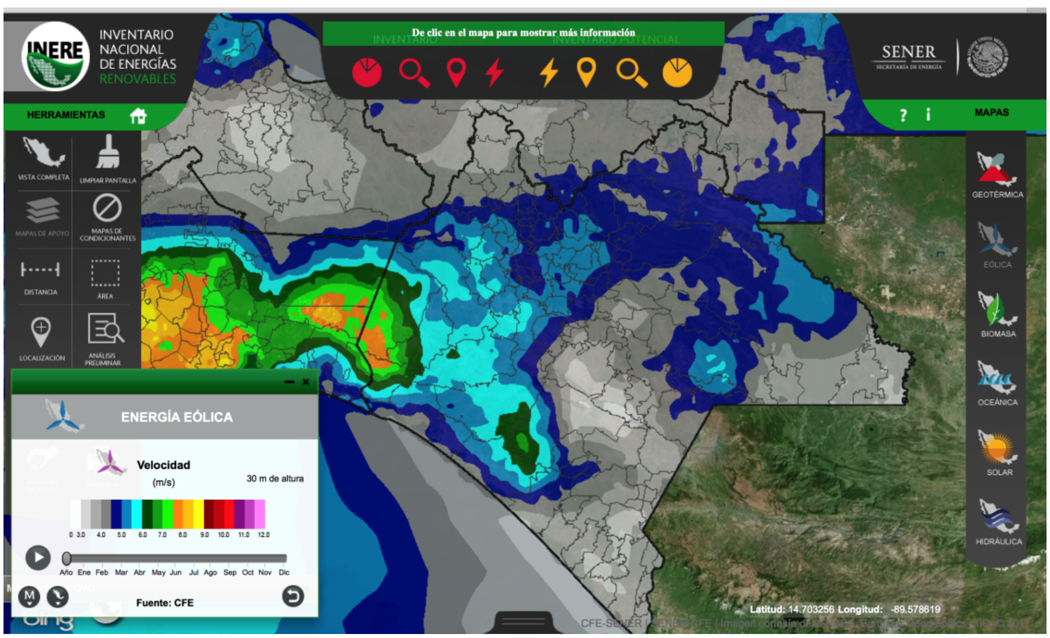


Sources: *USGS, <u>http://eerscmap.usgs.gov/windfarm/</u>*

NREL, <u>http://www.nrel.gov/gis/images/80m_wind/USwind300dpe4-11.jpg</u>

For the analysis, the northern part of Mexico is also dismissed since it could be more easily connected to the grid. On the remaining states, the selection was narrowed by identifying the locations with more wind potential, which are, in decreasing order: Oaxaca, Quintana Roo, Yucatán and Chiapas (INERE, 2016). As was already indicated, the states with the highest number of non-electrified households are Oaxaca and Chiapas. This research is focusing only in the State of Chiapas, see Figure 9, since rural communities could benefit from abundant commercial wind projects in Oaxaca, however, the framework used in this thesis could be used for other areas in Mexico.

Figure 9. Average wind speed at 30 meters in Chiapas

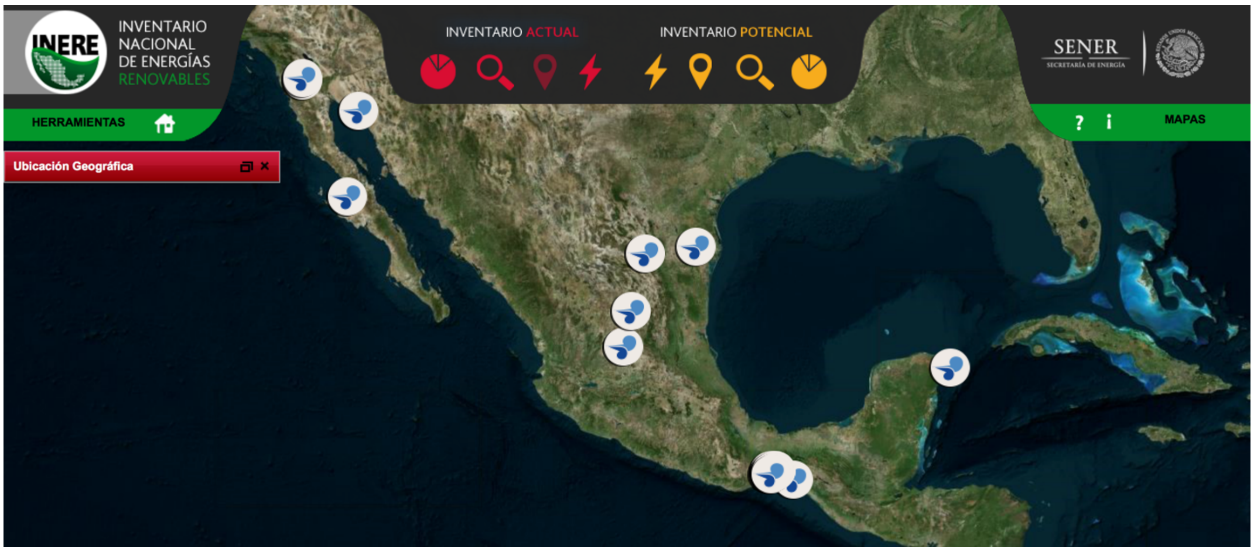


Source: Secretaría de Energía, 2016, Inventario Nacional de Energías Renovables, *https://dgel.energia.gob.mx/inere/*

Wind turbines are mainly located in the State of Oaxaca (92%). Chiapas has only 32 MW of wind capacity installed in the windiest area, located in the western area, near the State of Oaxaca, as seen in Figure 10 (SENER, 2016), where the wind speed can reach to up to 8 m/s at a height of

30 meters (INERE, 2016). The average wind speed in Chiapas has a range of 5-6 m/s at a height of 50 meters (IDE, 2014).

Figure 10. Location of wind turbines for electricity generation



Source: Secretaría de Energía, 2016, Inventario Nacional de Energías Renovables, https://dgel.energia.gob.mx/inere/

Solar resources

A solar PV feasibility study is not the main motivation of this thesis; however, it is also important to consider solar resources as an option to power the microgrids, since an analysis completed by the Rocky Mountain Institute (2014) concluded that the current decline of solar PV and battery storage costs, coupled with increasing retail electricity prices, will result in grid parity- the costs will decline to be equal to the retail cost of electricity- for residential and commercial customers in New York, California and Hawaii within this decade, and it will subsequently spread over all the rest of the states.

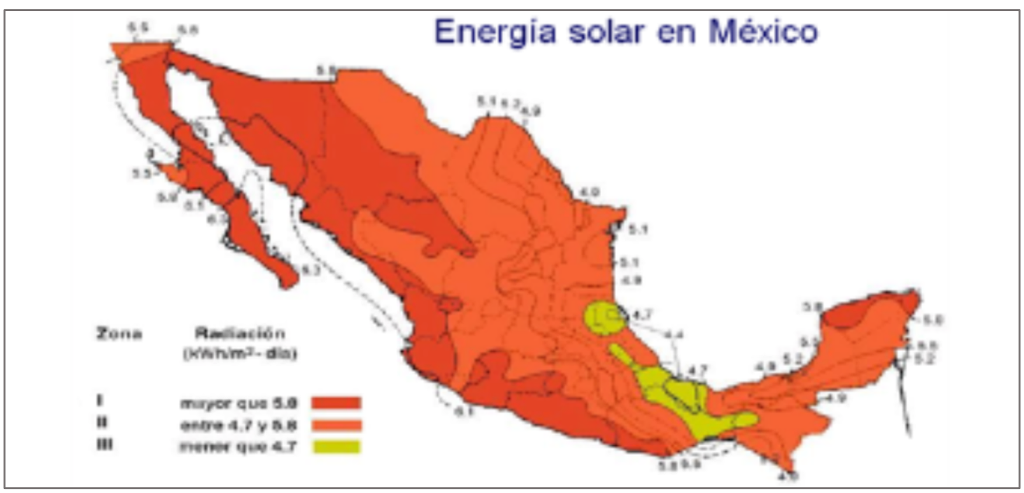
According to NREL's energy analysis (February 2016), the cost of PV microgrids with a smaller size of 10kW was US$3,897 with an O&M fixed cost of US$21 per year per kW, whereas, a wind related technology was US$7,645 with an O&M fixed cost of US$40 per year per kW.

Conversely, EIA's results (2016) suggest that wind energy solutions should have a broader distribution due to lower costs when compared to other renewable resources.

Research focused solely on wind energy options for microgrids was not found, whereas there is plenty of research focused on the application of solar energy for microgrids in Mexico. The thesis will explore electricity generation from solar resources only to determine if costs happen to be lower in the case of Mexico, when compared to a wind energy system.

Mexico's geographical location is appropriate for the use of solar energy (see Figure 11), since the average daily global irradiation in the national territory is around 5.5 $kWh/m^2/d$ (IDE, 2014). In Chiapas, the daily average radiation is 4.8 $kWh/m^2/d$, while the areas most favored by solar radiation are Arriaga with 5.4 $kWh/m^2/d$, and Tapachula and Tuxtla Gutiérrez both with 4.7 kWh/m2.

Figure 11. Irradiation map of Mexico

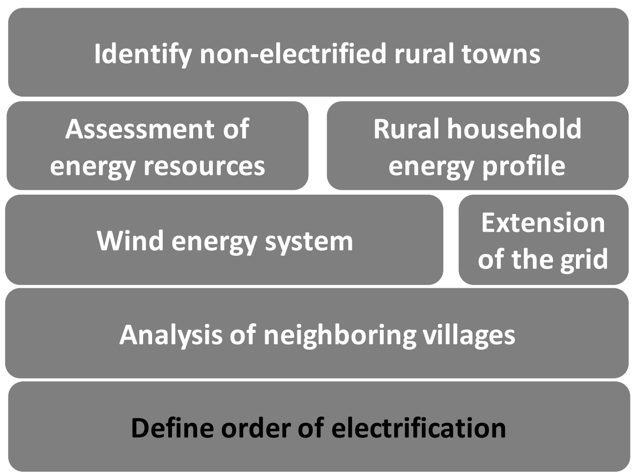


Source: DOF, Programa Especial para el Aprovechamiento de Energías Renovables, *http://dof.gob.mx/nota_detalle.php?codigo=5101826&fecha=06/08/2009*

Chapter 4: Framework

The general objective of this thesis is to determine the most cost-effective option to complete the electrification of non-connected communities in the State of Chiapas, Mexico, and sort them based on the optimal cost. The minimum cost between a wind energy system and an extension of the grid cost then becomes one of the considerations for the order of electrification. Figure 12 shows a schematic layout of the work taken as the framework for this thesis modified from Amutha (2016).

Figure 12. Framework for a cost analysis for NECs



The first step is to *identify non-electrified communities*, with specific characteristics, that will fall under evaluation. For the rural towns to be evaluated, a *rural household energy profile* must be defined, including a load profile, energy uses, and electric energy consumption. The next step is to make an *assessment of the wind and energy resources* in the towns to describe costs of a *wind energy system* by using an ad-hoc vba programming solution to test different sizes, heights, and capacity of turbines, towers and battery storage to reach the most cost-effective option for each town, when compared to the cost of an *extension of the grid,* determined by the distance to the grid and cost of equipment. *A model* for the *analysis of neighboring villages* is completed to determine potential benefits of grouping towns. With the information, an *order of electrification* can be established.

Chapter 5: Identification of non-electrified communities

In this chapter we determine all the communities that will be considered for a cost comparison between the two different options of electrification, which are the connection to the national grid or the construction of a microgrid: The microgrid can be either established for each town or for a group of towns. To complete the task, a series of filters must be established over existing data.

Description of data found

The sources of the information used correspond to the public agencies National Institute of Statistics and Geography (INEGI by its name in Spanish, Instituto Nacional de Estadística y Geografía), CFE, and the National Commission for the Development of Indigenous Villages (CDI by its name in Spanish, Comisión Nacional para el Desarrollo de los Pueblos Indígenas).

The latest housing and population Mexican census, Censo de Poblacion y Vivienda 2010, published by INEGI shows all non-electrified communities at the end of 2010; information for communities with less than 3 households is not included by INEGI for privacy reasons. There is not a public record of non-electrified towns to date. A myriad of villages has been electrified since 2010 (CDI, 2016). CDI's shared records help identify villages electrified in the past years, which are then eliminated from INEGI's base record for future analysis.

Much of the information used in the analysis is based on CFE's (2016) and CDI's (2016) unpublished record of electrified communities and plans of electrification from 2010 to date. The information was obtained through several requests to the National Institute for Transparency, Access of Information, and Personal Data Protection (INAI by its name in Spanish, Instituto Nacional de Transparencia, Acceso a la Información, y Protección de Datos Personales). The data provided was not complete enough to create a definitive, accurate and update list; however, the author intended to identify as many electrified towns as available information allowed.

An official record of towns with updated and detailed information is not available. A list of non-electrified towns would be helpful to determine local needs, develop monitoring strategies, determine benchmarks among microgrids for future research, propose new projects, secure funding, and monitor actual microgrids (Ubilla, 2014).

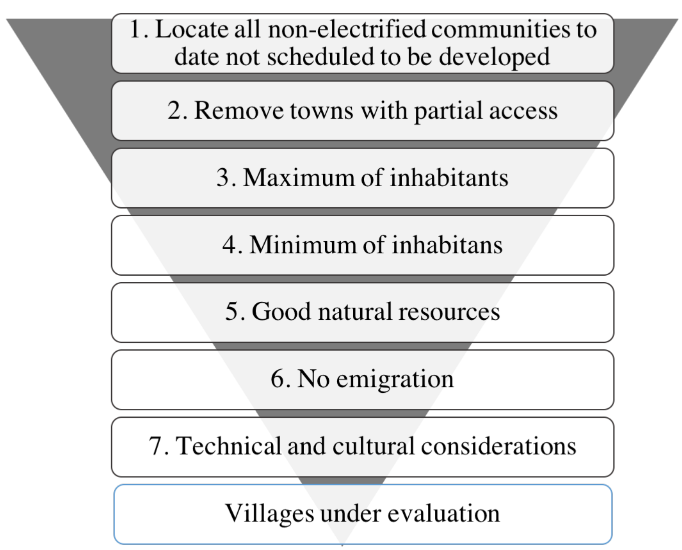
At the end of 2010, the profile of the resulting average rural village in Chiapas consists of 240 inhabitants, 54 households, less than 4.5 years of education, and two thirds of the population with native use of language, with a total of 20,047 towns. The aforementioned database includes towns that cannot be used in the analysis; the communities that do not match the requirements displayed in the following flowchart in Figure 13 will be ignored for the cost analysis. Each of the sequential steps are explained below.

Requirements to obtain final database

To find all the villages suitable for an analysis, a series of filters must be applied to initial databases to create the list of towns to be evaluated; a framework must be followed for this purpose (Ubilla, 2014). As previously indicated, the analysis is applied to information obtained through many sources, but the resulting record might include towns already electrified due to a lack of complete information.

The filter is described in the following sections, which correspond to Figure 13.

Figure 13. Diagram to identify NECs in a given area



1) Locate all non-electrified communities

To begin, a record was found of these towns: not connected to the grid (INEGI, 2010); not connected to date, but scheduled for connection (CDI, 2016); and, of those that are not scheduled to be connected (CFE, 2016). This step aims to disregard every location that has energization related projects in any stage, and identify locations that do not have any energy solutions in planning stage, in this case until 2018. Communities with less than 3 households were also discarded, which represent 9,041 towns. The number of remaining towns after the filter was 10,005.

2) Remove towns with partial access

Only communities with a complete lack of access to electricity were included. Individuals choose not to connect to the grid for different reasons other than its availability, therefore, there might be towns with the technical opportunity to connect to the grid where a large number of individuals choose not to do so, individuals in rural areas might not be able to afford the electric devices or be able to pay the electric fees. The analysis focuses only on that towns that have no access to the grid. Only 841 towns met the requirement.

3) Maximum of inhabitants

The next step is to select those villages with less than or equal to the minimum number of inhabitants that are included in the immediate electrification objectives of the government, which in this case is 100 individuals. CFE and the federal government focus on towns with more than 100 individuals, which leaves small non-electrified towns without electricity for a longer period. There are 786 non-electrified towns in Chiapas in 2010 that had less than 100 inhabitants. There were only a few with more than 100 individuals than remained unconnected.

4) Minimum of inhabitants

A minimum of population is set according to previous studies. A minimum of 10 homes is required for economic feasibility, according to The Chilean Centre for Energy (CE, 2013). Only

150 of the total towns remained. There were 123 houses with 7, 8, or 9 homes, which could be analyzed on a future occasion.

5) Good natural resources

The analysis should consider only those locations with enough supply of wind and solar resources to host a microgrid. For Mexico, Martinez (1987) found that with the exception of solar energy, minimum energy-resource requirements are above the national mean values of resource and so the requirement of good natural resources would restrict the implementation of these systems. After a minimum requirement of 4.5 m/s of wind speed to select a state, for every location in Chiapas, the wind speed required as minimum was of 3 m/s with a height of 30 meters, based on technical specifications for start-up wind speed (Bergey, 2017). For every location, the wind speed was found specifically. The author could not find a public database for every specific location in the country. None of the locations showed a wind speed less than 3 m/s.

6) No emigration

The requirement ensures that O&M know-how is maintained. The maintenance and operation of wind systems is more intensive and less autonomous, and CFE employees are not required to work in areas of difficult access, without infrastructure or risky in nature, as indicated in the agreement between the union and CFE (CFE-SUTERM, 2016-2018). The author talked to employees assigned to field activities, and confirmed the application of the agreement. This might be one of the reasons of the wider deployment of solar panels when compared to wind turbines because of the relatively smaller amount of maintenance required for solar panels.

The population reported for every town can be reviewed during each housing and population Mexican census until 2010 in INEGI's website (2017), since the rate of emigration is higher than the population growth rate (CONAPO, 2014).

A total of 23 villages were omitted after filter 6.

7) Technical and cultural considerations

For the following reasons, the communities, or at least a representative sample based on the geographic characteristics of them, should be visited in order to obtain an accurate list of potential candidates to locate a microgrid: a) Determine technical feasibility, for example, turbulence over a wind turbine can reduce its service life, so it should be mounted so that the rotor's bottom edge is 10 meters above and 100 meters away from any obstacle at a minimum. It is also important to verify the existence of the required infrastructure to transport the equipment into the community; Figure 14 shows mules transporting PV modules to remote sites in Mexico. (NREL, 2003); b) Based on the results by Burlig (2016), villages should have a real potential to start activities with a higher level of productivity with the use of electricity to have a net positive effect.

Figure 14. Transportation used to carry solar panels in Mexico

Source: National Renewable Energy Laboratory, July 2003, Renewable Energy for Water Pumping Applications in Rural Villages, http://www.nrel.gov/docs/fy03osti/30361.pdf

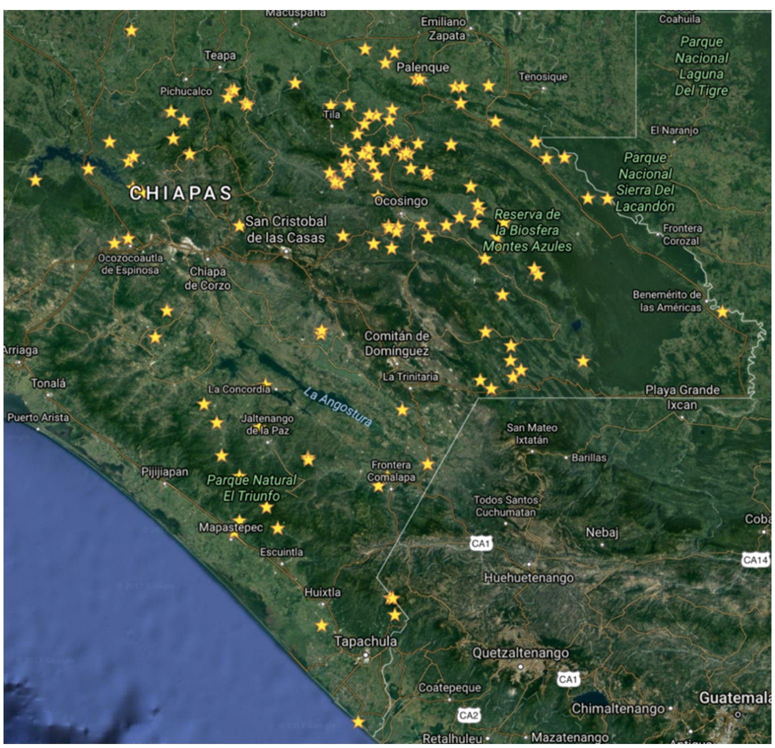
This requirement was not applied in the present analysis, and the status of specific and real conditions for every particular location were not defined. The only possible way to complete the abovementioned assessment is visiting the communities, which is beyond the scope of the thesis.

Villages under evaluation

The first and second requirements should be straightforward with a complete database. The third requirement is selected according to the public policy in place. The fourth requirement helped narrow the communities under the scope of the analysis; it could be eliminated in case there was an accurate database of natural resources for every town in Mexico.

After applying the filters, the list of communities electrically isolated with the minimum requirements necessary for the development of micro-network projects is obtained for Chiapas. All the 127 towns that passed the filters are shown in Figure 15. Non-electrified communities are spread across the state, and few of them are located in the windiest places. A typical rural non-electrified village is characterized by having 66 habitants, 14 households, 3.6 years of education, and two-thirds of the population uses a native language in average.

Figure 15. Location of NECs under evaluation in Chiapas



Chapter 6: Rural household energy profile

A Non-electrified rural community (NEC) is defined as all the people who live in a particular area, constituting a settlement, village or town, without an electrification system or with an alternative insufficient electrification system. In this thesis, only NECs with less than 100 individuals will be under evaluation. The definition is created to define the villages under the scope of this analysis. This definition is more restrictive than that used by INEGI (2016), which considers 2,500 individuals as the threshold in population between a rural town and a city.

It is not the case that households without access to the electricity service from the grid do not use electricity; instead, almost all households have certain form of off-grid electricity use; in the current analysis, unconnected communities and communities without electricity are used interchangeably, including households under the scope of this thesis.

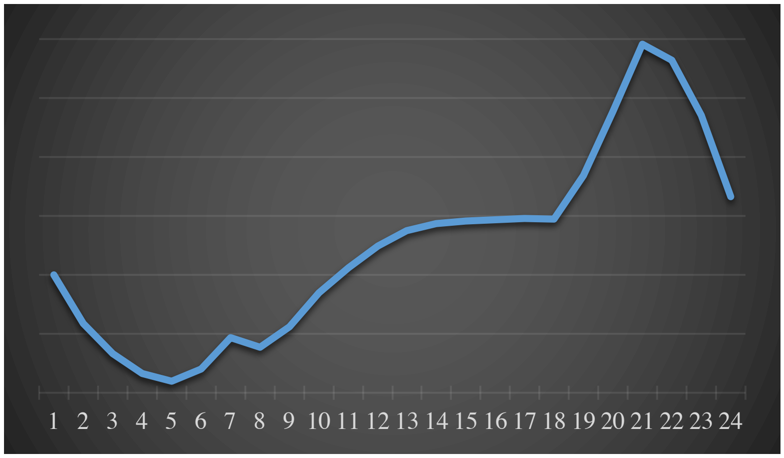
A description of the load profile and the electricity demand by NECs must be established in order to describe a power system for each of them. Currently, there is not sound data about the quantity and pattern of the electricity used in the rural areas of Mexico.

Load profile description

Electricity consumption in Mexico is aggregated in areas by the CFE. The State of Chiapas is included in the "Oriental" group. Without specific information about every town, the first option to create a typical load would be using electricity consumed in the Oriental area profile (SENER, May 2016). The information is very detailed with respect to time, but it does not separate rural, urban and industrial expenditure, see Figure 16.

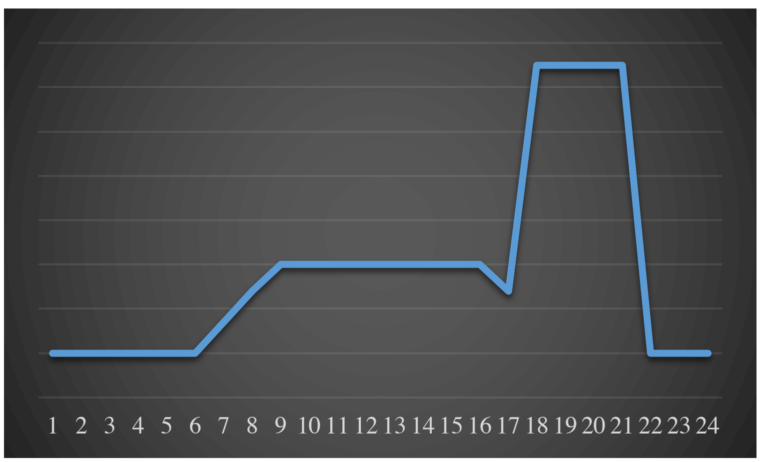
An alternative method is generating the electric-load curve in Figure 17, from a typical rural profile created by IEA (2013) that describes the pattern of consumption of new areas pending to be electrified. In comparison, both curves show the same pattern, and IEA's curve illustrates a higher consumption peak in the late afternoon, which might require additional equipment to meet the demand. IEA's load curve will be used in this analysis because it does not incorporate urban areas.

Figure 16. Average hourly consumption profile of electricity for the Oriental area for one year



Data from: Secretaría de Energía, May 2016, Base de datos de demanda horaria para PIIRCE 2016-2030: Programa de Desarrollo del Sistema Eléctrico Nacional.

Figure 17. Typical load profile in rural areas



Data from: International Energy Agency, 2013, Rural Electrification with PV Hybrid Systems, https://www.iea.org/media/openbulletin/Rural_Electrification_with_PV_Hybrid_systems.pdf

To provide a magnitude to the load profile an energy consumption must be determined.

Electric energy consumption

There is no public information about the electricity consumed by each town in Mexico. The electric energy consumption used for planning purposes by the CFE (2016) is 95 kWh a month for every rural household at the moment of the evaluation, according to unpublished information obtained through the INAI, Mexico's institution supporting the right to information. The estimation was made based on historical, and bigger, projects in countryside zones, and it has been used for previous projects related to microgrids powered by solar systems (Greenergy, 2013).

According to Martinez (1987), rural populations use only 31.6 kWh per month per household; the estimation would cover water pumping for irrigation and consumption, and the use of domestic devices like a refrigerator, TV, radio, iron, and a sewing machine. The amount increases if more productive uses are considered, such as the use of a blender, mill, or motor for a cottage industry; the assumptions made about the appliances used and individuals sharing them were confirmed by the author of this thesis with field employees of CFE. The estimation was updated with current electricity consumption of appliances.

As seen in Table 1, the estimated consumption by CFE represents two or three times when compared to the other three references. An assumption of this nature implies an excess of infrastructure.

Table 1. Electricity consumption of rural towns

Reference	Electricity consumption (kWh per month)
CFE (2016)	95
Martinez (1987), updated	33
The World Bank (2010)	35
SNV (2013)	46.2

The estimation published by Martinez (1987) was updated with current electricity consumption of appliances, and it is used in the analysis.

U.S. electricity consumption per household per month is 901 kWh (EIA, Oct 2016), which represents around 30 times that of a rural town; such low consumption can only be understood by exploring the energy uses of rural small towns.

Energy uses

The World Bank (2010), as part of the Energy Sector Management Assistance Program, conducted a Survey covering 6,690 households with and without electricity, approximately 51% of them located in the rural areas of Peru. The study had important findings that are useful to increase the understanding of other communities under the same conditions in Latin America:

a) 86% of all households without electricity used dry cells, mainly for small appliances (e.g. radios and flashlights), 80% used kerosene and 86% used fuelwood for lighting. For household use in Mexico, firewood is consumed as fuel in 95% of households, while only 4% of individuals use electricity; the principal use of energy in rural communities is for cooking, water pumping and irrigation. (Barnes, 2005);

b) Households in the lowest quintile spend about 17% of their total monthly expenditures on energy, and 39% of it is for lighting. Therefore, rural households need an affordable solution that helps reduce the substantial share of income devoted to their energy uses;

c) Only 0.6 and 0.8% of rural households use small gasoline or diesel generators, and solar systems, respectively, probably due to high upfront costs and the limited help of donations. This is the reason why the problem of electrification must be solved by not necessarily relying on the households' purchase power and credit options;

d) Social benefits were not considered, such as reduced burns and respiratory effects from kerosene, but it was found that children studied 15 minutes more per night when provided with electricity;

e) The average consumption in 374 electrified villages of any size was 35 kWh per household a month, with an expected growth of up to 1% per year. The rate of growth stated in the study will be used as an input in this analysis.

Within the communities with technical access to electricity, not all of the residents benefit from the infrastructure, some of the reasons are the lack of electrical equipment, and insufficient resources to pay the electric bill. For example, in Chiapas, in the cities other than those without complete access to electricity, the weighted average of houses not using electricity is 12.6%. This means that electricity consumption should be reduced in such percentage to have a better estimation. A penetration level of 87.4% will represent the maximum use.

The load profile, energy consumed and the information aforementioned helped determined the electric energy consumption for 30 years of every NEC in Chiapas.

Chapter 7: Cost of a grid extension

The traditional option for electrification is a grid extension. The cost-benefit analysis defined here for the connection to the national grid depend on the following concepts from the utility's perspective:

a) **Income**: *Electricity rates* multiplied by *effective energy demand*. As explained before, CFE estimates income based on an energy demand that does not meet reality, both because electricity is not affordable for all rural individuals, and also because the use of electric devices is more limited than in urban areas.

b) **Costs**: *Distance to the nearest electrified town* multiplied by *cost per km (D) + cost of a transformer (T)*. The location of electric facilities as well as a detailed map of the grid is not available for national security reasons, hence, accurate measurements of the distance of the grid extension to connect each town is not available. The distance from each NEC to the nearest electrified town was measured, and it was used as a proxy to represent the length of a distribution line that would be needed to electrify the town. The average distance to the nearest town was 3.15 km, that is, 1.96 miles. The cost per kilometer for a single-phase distribution line, 13kV, 1/0-line pole made of concrete for rural areas was USDeq$7,966 (CRE/CFE. 2013); it includes cost for materials and equipment, permanent installation, workforce, design and supervision of the project, and cost of retirement. The span of the study was determined based on a conservative estimation of the service life of poles (Nevada, 2015) that matches tough weather conditions in rural Mexico. The distribution line considered has the lowest specifications that CFE uses and the least cost, however, it has idle capacity and therefore an over-investment is realized. Quotes for single-phase 10kVA transformers from two companies in Mexico were obtained, IG and Prolec-GE, and the average cost was used. The transformer meets the maximum peak power for all towns. Therefore, the cost does not depend on the load, because of the small size of energy used and the equipment used by CFE. The analysis did not consider system losses, support services, or operational, financial and security risks. Cost for a radial distribution network is not taken into account since all systems are supposed to imply a similar burden.

c) **Variable costs**: Present value of generation costs (G) of USD$.1 per kWh, including fuel, (El Financiero, 2013) plus 3% of total installation costs for O&M (O) annually for 30 years (FQC, 2013), which is the evaluation period considered.

A standard present value method was used to perform the economic comparison between the various systems here mentioned based on Martinez's calculation (1987), $(D+T)+\sum_{n=0}^{30}(G+O)\left(\frac{(1+g)^n}{(1+d)}\right)$. The costs previously mentioned were taken into account. With respect to the growth rates used for the calculation for both systems, the calculation used a discount rate and expected return of 8% (d), as used by CFE (Feb 2015). It was assumed that the rate of growth for the fuel costs, the O&M, and solar and wind energy systems (g) equals the discount rate. It has also been also assumed that this system is easy to maintain and there will be no restoration costs or other expenses besides the ones mentioned here. With respect to the use of land, typically CFE does not pay for the presence of poles and lines on private property.

$$(D+T)+\sum_{n=0}^{30}(G+O)\left(\frac{(1+g)^n}{(1+d)}\right)$$

All costs shown in the document are in USD. Costs originally in MXN are converted into USD at the exchange rate as of December 31, 2016. Costs are rounded to the nearest unit.

For the expansion of the grid, the average present value of the cost to electrify a household today was US$4,971.

Chapter 8: Cost of an independent system

Now we can use the information we have gathered about the energy use in rural towns to evaluate the cost of a renewable energy system for every NEC. This thesis will focus in evaluating a wind energy system as an alternative for electrification; however, solar PV was also considered to determine the viability of the wind system based on the system costs. Additionally, according to EIA's (2016) Levelized Cost of Electricity analysis, solar Photovoltaic (PV) technologies currently show, and are expected to show in the future, higher costs than wind turbines, thus, the relevance of focusing on the latter. The cost of wind plants entering to service in 2018 per MWh is $58.3, with a minimum and a maximum of 41.3 and 71.3, respectively (EIA, 2016).

Furthermore, no previous study was found using only wind turbines to power microgrids in Mexico, nor research to provide electricity to a large number of towns, or data about small scale wind systems in Mexico. Therefore, the analysis must start from basic data.

Wind energy system

The major components of a wind energy systems are: a rotor with blades, which transforms the wind into mechanical energy onto the rotor shaft; the gearbox to pair the rotor shaft to the electric generator; the tower which supports all previous components above the ground to capture wind speeds; a firm foundation; a control system to activate and deactivate the turbine and to monitor the operation; inverters and controllers to convert DC power into AC power, and manage the energy storage and deliver power to the load; in this case, batteries to provide energy when wind is not blowing sufficiently enough to meet the demand (World Bank, 2007).

The energy generated and its associated cost, including the battery bank, was determined after varying the main parts of a microgrid, that is, the height of the tower and the size of wind turbines. The cost-benefit analysis is as well from the utility's perspective.

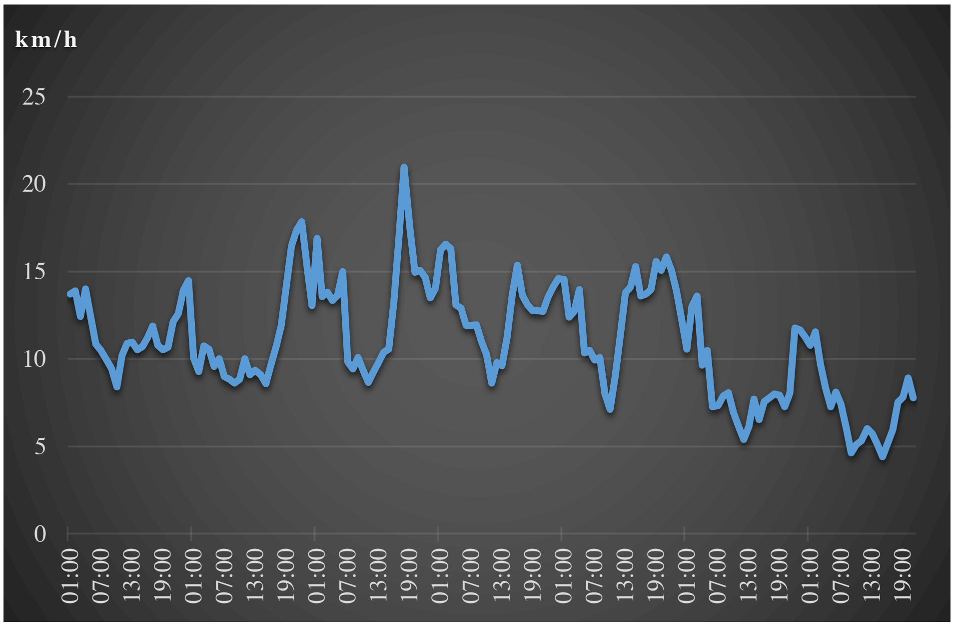
a) **Income**: *Electricity rates* multiplied by *effective energy demand*. The income for the utility is the same for any option of electrification, since the analysis does not consider, for example, the payment for the local population working in O&M activities. Therefore, only costs are compared.

b) **Costs:** The key factors that determine the size of the system and the present value of the cost of the microgrid (M) for every town are the *effective demand, wind resources, the height of the tower, the turbine size, and the battery storage,* with a lifetime service adjusted to 30 years, according to the technical information of the size of each wind turbine.

The wind speed is the most essential input. Information of the wind speed for the location of each community in Chiapas it is not available, therefore the following procedure and assumptions were followed. The wind speed at 10 meters from 01/10/2017 to 01/17/2017 was obtained from the meteorological stations in Chiapas. A weekly wind speed profile for Chiapas was created using the hourly average of all stations (see Figure 18). It was assumed that every week the wind speed versus time will have the same profile as the one captured in middle January. The wind speed profile for every location was determined by using the wind speed profile of Chiapas. Every hour (H) for each location (L) was multiplied by a factor related to that location (FL). The factor reflects how windy the location is in comparison with the whole state, FL = (average annual wind speed in L/ average annual wind speed in Chiapas). For more precision in the calculations, an anemometer should be installed on a flat terrain in each town with no obstacles, and measurements should be taken every 10 minutes for more than one year; granular data will provide a more accurate result. In addition, as shown in Figure 19, the wind speed during winter is relatively higher than the rest of the months, which will cause generation to be overestimated. Another approach was also explored: the electricity generation for every town was estimated by adjusting the weekly data obtained from meteorological stations to the annual average for every location, that is, scaling the time series of the wind speed so its average matches the average from the weather stations; the average wind speed for the non-electrified towns is 4.8 m/s. In that case, the generation was highly underestimated since the equation to calculate the power converted from the wind into rotational energy *elevates v to the power of 3,*

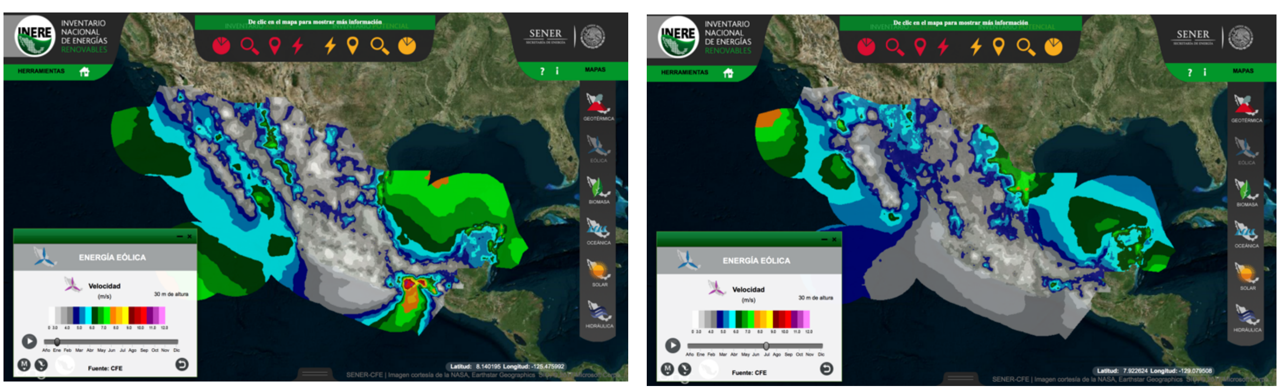
$1/2pAv^3C_P$. This second approach was dismissed for the high miscalculation of this estimate.

Figure 18. Wind speed profile at 10 mts for weather stations in Chiapas from 01/10/2017 to 01/17/2017



Data from: Servicio Meteorológico Nacional, Comisión Nacional del Agua, http://smn.cna.gob.mx/es/emas

Figure 19. Wind speed at 30 meters in Mexico during January (left) and July (right)



Source: Secretaría de Energía, 2016, Inventario Nacional de Energías Renovables, https://dgel.energia.gob.mx/inere/

As of the end of 2013, more than 227 MW of small wind power capacity was installed in the United States (WWEA, 2016). The average capacity of a horizontal-axis model was estimated at 10.8 kW (IEA, 2016). Data for small wind turbines will be used for this analysis. Small wind turbines, with a rated power of less than 100 kW, have been widely used for electricity storage and supply in rural towns, particularly for off-grid electric supply. The analysis was completed using from one to 50 horizontal-axis .45kW turbines, a 1kW turbine, two 1kW turbines and a 7.5 kW wind turbine. Energy companies Bergey (2013) and Aleko (2017) publish complete technical and cost information data; therefore, data from both companies were used for the cost analysis, quotes, and equipment. Bergey products are turbines above 1kW, and Aleko products focus on the .45kW turbines, with 30 and 5 years of service life, respectively. When turbines are compared, besides the difference in size, there is a large difference in the cost, service life, and the height of tower they use. For the analysis, it was not taken into account the capital recovery factor nor the controllers.

The height of the tower is also a key factor that determines the energy generation of small wind turbines. To reduce the negative effects of turbulence and benefit from a higher wind speed, a taller tower is better; however, it has a higher cost. Additional innovation to reduce costs at lower heights is a key goal for the development of small wind technology (EIA, 2016). Most small-scale wind turbines are below 30 meters in height (IEA, 2016) due to high costs in increasing above that height. For the following analysis, the range of heights considered was 10 to 30 meters; the power law equation was used to scale the wind speed at different heights (Kubik, 2011).

Cost of turbines and battery storage are affected by the generation (height, wind speed) and hourly consumption. A bank of Rolls batteries is considered for the costs to complement the off-grid system, which can be wired to increase the voltage or the amp hour capacity of the bank. The quote in Mexico of the 6 Volt 4000 Series, with a capacity of 530 amp hours and 640 Cycles at 100% Depth of Discharge, was USDeq$.18 per kWh, obtained and updated from Guzmán-Escoto (2015).

All remaining costs used are detailed in Table 2. Notice that to reach the same capacity of a 1kW-wind energy system, around 13 .45kW wind turbines are needed due to the short service life of the latter.

Table 2. Relevant costs of a microgrid

Component	7.5 kW wind turbine	1 kW wind turbine	.45 kW wind turbine
Cost of turbine (USD)	26,870	4,595	399
Service life of turbine	30	30	5
Tower (mts)	14,145	3,130	399
Installation and electrical equipment (USD)[2]	9,023	1,699	175
Inspection and maintenance, each year (USD)[3]	50	50	50

1. *The 7.5 kW and 1kW turbines are held by towers with an elevation of a 30 mts, while the .45kW turbine requires a tower with 10 meters of height.*
2. *National Renewable Energy Laboratory, 2014, Cost of Wind Energy Review, http://www.nrel.gov/docs/fy16osti/64281.pdf*
3. *US Department of Energy, 2007, Small wind electric systems, http://www.nrel.gov/docs/fy07osti/42005.pdf*

c) **Variable costs:** Present value of O&M of the system (Bergey, 2012).

d) **Other income/expenses:** Wind energy systems also imply other economic and non-economic benefits not considered on the economic valuation shown here, over fossil fuels. Environmental benefits (i.e. value of Clean Energy Certificate, benefits to society for using low carbon technologies), employment for O&M, and other concepts were not considered in the calculation. We did not consider costs related to permits, and contingency payments. Keep in mind for these costs that the availability in the future of various incentives, including state or federal tax credits, can also impact the calculation.

The energy generated for every hour of the day for one week was calculated by using the parameters of Air density, ϱ = 1.23 kg/m3, and Power Coefficient, Cp = 0.4, suggested by the Royal Academy of Engineering (2007). In Table 3 the results for the annual energy output in average for every size of wind turbine. The resulting electricity generation shows a minimum level at around 10 am, and a maximum at around 6 pm to midnight.

Table 3. Energy output by turbine size

Wind turbine size (kW)	Annual Energy Output (kWh)
7.5	131,866
1	16,820
.45	2,839

By using the load previously defined, the hourly, H, consumption was determined for each town, and compared to the electricity generation with a wind turbine. The problem was defined as to find the minimum wind energy system cost for each town, $f\,(\text{height, turbine size, pv capacity, battery storage})$, with the restrictions of providing enough power to the town for one week, 168 hours, $\sum_{\mathrm{H}=0}^{168}(\text{Energy generation}_{\mathrm{H}}) \geq \sum_{\mathrm{H}=0}^{168}(\text{Energy consumption}_{\mathrm{H}})$, and to have sufficient battery capacity by using $\min(\sum_{\mathrm{H}=0}^{168}(\text{Energy generation}_{\mathrm{H}} - \text{Energy consumption}_{\mathrm{H}}) \leq 0)$ for any subset of consecutive h hours.

The minimum costs were reached with a height of 30 meters- about twice the height of a neighborhood telephone pole, mainly with 1kW turbines and with limited battery storage.

For the microgrid, the average present value of the cost to electrify a household today resulted as US$1,853.

Solar Photovoltaic system

To calculate the electricity generation from solar, the PVWatts Calculator (v.5) by NREL was used and the closest station to Chiapas was chosen, located 40 miles away in Guatemala; the geographic and radiation conditions are similar to that of Chiapas. The same radiation was applied for all towns due to its homogeneity in the region (see Figure 11). The PVWatts has access to different databases including the National Solar Radiation Database (NSRDB), 1961-1990 data (TMY2), 1991-2010 update (TMY3), and EnergyPlus weather files. PVWatts Calculator takes the specifications shown in Table 4. A fixed (open rack) was chosen, due to a higher grade of maintenance in moving arrays. The resulting annual solar radiation was an average of 5.53 ($kWh/m^2/d$) for 1kW of DC system size (NREL, 2017), that would generate 1,504 kWh of energy for one year. The energy generated for one week in January, similar to the case of wind, was used as input to determine the size of the system for every town such that the cost of the system, including battery storage, would cover the energy requirement of the town and that it would be less than building an extension to the grid. The cost for every 1kW-system was assumed as US$2,930, which included the modules, inverters, installation labor, tax, overhead, and others (NREL, 2016).

Table 4. Inputs used for simulation

Wind turbine size (kW)	Annual Energy Output (kWh)
DC System Size (kW):	1kW
Standard (crystalline Silicon) efficiency	15%
System Losses (%):	14%
Panel tilt	20◦
Azimuth (panels facing south)	180◦
DC to AC Size Ratio:	1.1

Source: National Renewable Energy Laboratory, 2017, PVWatts Calculator, retrieved January 29, 2017, http://pvwatts.nrel.gov/pvwatts.php

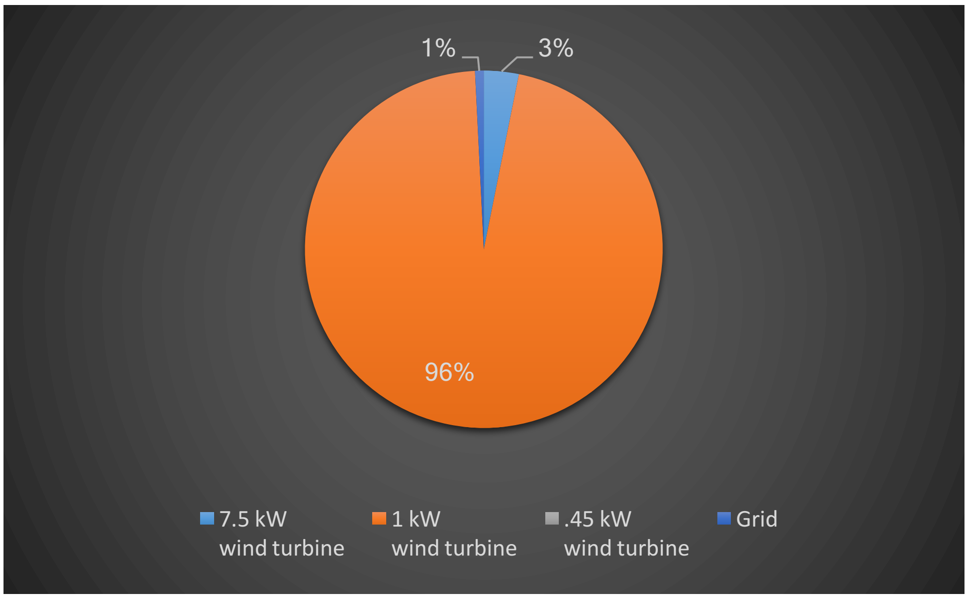
A better estimation could be achieved with more granular data for every town, as well as in the case for the wind energy system. A related research found that a combination of solar based microgrids and wind based microgrids rendered best results, taking advantage of best wind resource areas (Ranaboldo, 2015). Hence, it is important to study hybrid systems for a future occasion.

Chapter 9: Comparison of costs and verification of results

Cost-comparison

Based on the electrification cost for each town, the cheapest option is chosen so that each village has its own energy system with the best solution. The percentage of the number of towns using every type of technology is shown in Figure 20.

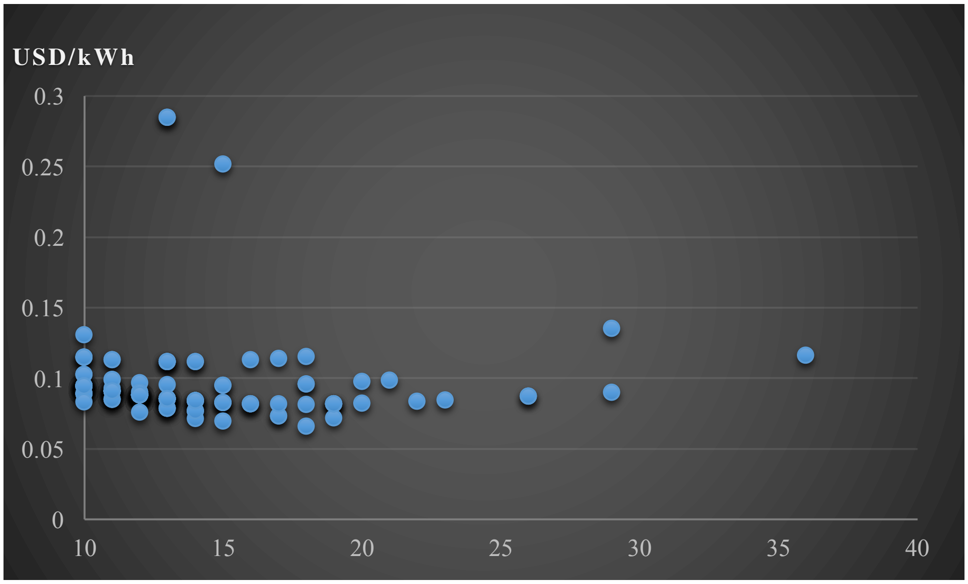
Figure 20. Use of grid extension and wind energy systems



The average costs for the two options shown in the previous sections are reflected in the results. For 99% of towns, the best option is to use a microgrid with 1kW wind turbines, because .45kW turbines imply high costs in batteries and 7.5kW turbines have an excess of capacity for most towns.

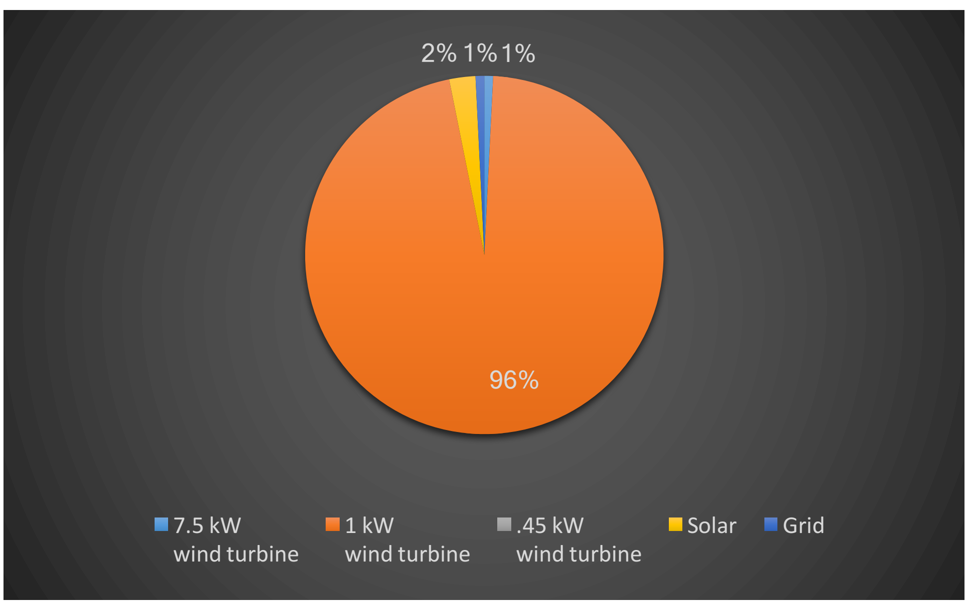
The resulting average cost per kWh for the best solution in every town is USDeq$.095, or USDeq$95 per MWh. The results for every town is shown in Figure 22. The highest USD/kWh ratios are caused due to a low local wind speed and a long distance to the grid.

Figure 21. Cost of electricity per kWh for all villages with the best solution



The above results were obtained with wind as the only renewable option. If solar photovoltaics are added as an option to the mix then the results did not change drastically as shown in the next figure. The main effect is that the 7.5 kW wind turbines are substituted by solar panels.

Figure 22. Use of grid extension, wind energy systems, and solar panels



As described above, the results showed that almost for all NECs it was not a cost-effective solution to either electrify them by using solar PV or by building an extension to the grid. The best option based on costs is to implement a microgrid with wind turbines.

The main findings of a sensitivity analysis revealed that: (i) The difference in results from both renewable sources, wind and solar, come from their match with consumption and reduction of batteries. A decrease of 30% in the cost of batteries increases the relative costs of the solar systems, although not significantly, increasing its participation to 5%; (ii) CFE is required to cut costs significantly, in half, to become the best option in 17% of the towns; (iii) A substantial rise in the cost of wind energy systems does not affect its participation substantially, which could come, for example, from the expenditure of introducing a training program for local inhabitants. If the wind energy system increases by 30-50%- or solar reduces by 30 to 50%- then the grid is marginally more attractive and solar presence remains almost the same.

Other references

The cost for the wind energy system had to be built specifically for Chiapas, since most publications focus on larger systems or on microgrids powered by solar PV. Table 5 summarizes the closest direct references found, however they are different in scope or include larger facilities.

Table 5. Cost of wind energy systems

Reference	Cost (USD/MWh)
WWEA's installed cost (WWEA, 2016)	6,230 (USD/kW) [1]
IEA's LCOE (IEA, 2016)	150 - 350
CENACE (PWC, 2016)	42.7
EIA's LCOE (EIA, 2016)	58.3
LCOE for Mexico (EMIS, 2015)	71 – 135

[1] *All costs are in* USD per MWh, except for the first reference, which is in USD per kW.

The first row indicates the average installed cost of new small wind capacity installed in the USA in 2014. The amount is lower than the one used in this analysis, namely \$9,475, which was obtained from actual quotes.

In the second line, IEA results are shown for small turbines. IEA defines them with a rated power of less than 50-100 kilowatts, which is significantly larger than the power needed for rural towns.

The third row belongs to large scale wind farms in Mexico. Renewable energy developers were assigned contracts by the National Energy Control Center (CENACE) to produce power in Mexico during the country's first private auction during 2016. The first auction of long-term power purchase was public and prices offered per MWh for each type of technology were recently also made public upon request. The prices include all costs and the return required by the companies to remain profitable too. The average price for wind power was \$42.7 USD/MWh with a capacity 78.8 MW; it includes a penalty or reward based on the location of the source and the need of electricity in that region, and also green bonds (known as CELs) for the generation of electricity from clean sources.

The fourth and fifth references indicate the Levelized Cost of Electricity (LCOE) of large scale farms for Mexico and the US, respectively. The cost in México is significantly higher. Both estimations do not match the result in this analysis and the results obtained by CENACE.

For solar, this analysis rendered a higher value than a project completed by the World Bank (WB). The installation costs for solar are 57% above World Bank's solar systems installation costs. In the project, called Energy Integrated Energy Project, the WB worked with the Mexican government to provide electricity to rural communities far from the electricity grid. The WB funded the rural electrification program, the Mexican Department of Energy, SENER, coordinated the project, and CFE completed technical activities. The project started in 2012 and lasted for 3 years, considered to have the largest number of installations for actual use of any project (World Bank, 2016). The WB allowed wind and solar energy systems as part of the bidding process, considering them price competitive. The companies that won the bidding process focused on solar energy systems, having no offers for wind energy systems. A total of 2,235 households were electrified under the rural electrification program with costs of USD$1,535 per household, including battery, lamps, mounting, wiring, installation, etc. 2,357 kW of new renewable capacity was actually installed, that represented less than 40% of target (World Bank, 2016). The difference in results can be due to our focus in small towns, which increases the cost of electrification per family. As seen above, even if the cost of a solar system is reduced in 50% the solution of the optimum system remains almost the same.

Chapter 10: Methodology for a group of villages

Now that the evaluation is complete for every individual town, groups of them will be considered together to see if grouping can result in benefits. Towns can benefit from being a member of a group of towns for multiple reasons, such as, (i) wind power capacity may be built and planned less expensively using larger turbines as opposed to installing more smaller turbines (DOE, 2016); (ii) use interconnections to other towns; (iii) wind resources can be sited in the towns with the best wind resource. In Chiapas, non-electrified towns cannot benefit from economies of scale using larger wind turbines since they are not typically close to each other; however, they can benefit from the other factors.

The first issue to consider is the maximum distance to define a neighboring town for every village; if 1 mile is the limit, only a few villages will create a group, whereas if 100 miles is the limit, there will be several combinations of groups. A village will only form a group if the interaction reduces its current optimum cost. The optimum cost that resulted for every independent town was converted into equivalent kilometers of extension of the grid, “equivalent distance”, by using the cost of building a distribution line. In order to define a town as a neighbor, the *equivalent distance* between towns must be less than the real distance. In case that the cheapest option for a town was to build an extension to the grid, the equivalent distance would stay the same as the real distance. The equivalent distance was then used to identify all neighboring villages in a shorter distance, and villages who were close enough were grouped.

When towns are considered as a group, the electricity demand is aggregated and a new cost is generated based on the improved wind speed, the new wind system, and battery cost associated. The distance was calculated between each town and other neighboring non-electrified villages; those towns that faced a lower cost to complete a connection to neighboring towns than the cost of their optimal solution on their own were put together as a group. The group will be able to share facilities, and natural resources.

For a large number of villages in a group, to determine the optimal mix of technologies, the allocation of technology for every town and group of towns will be defined as a pure binary integer programming problem based on a facility location characterization model (Bradley, 1977; Campbell, 1994).

If x is 1, for $i, j, k, l = 1,2,3,4, \ldots$ then towns i, j, k, l are electrified by connecting them to the grid; if x is 0, such towns are not connected to the grid. Similarly, if y is 1, for $i, j, k, l = 1,2,3,4, \ldots$ then the towns form a group and are electrified by using a wind turbine. If y is 0, the towns do not form a group powered by a wind turbine, that means that either they will be connected to the grid or own their own turbine. n indicates the number of towns in a group. Notice that the order of i, j, k, l is not relevant, and, for example, $ijk=jki$.

For $n= 4$, the objective is to

Minimize:

$$\sum_i x_i(c_i + VC_i - lg_i) + lg_1 + lg_2 + lg_3 + lg_4 + \sum_i \sum_j \sum_k y_{ijk}(lg_{ijk} - lg_i - lg_j - lg_k) +$$
$$\sum_i \sum_j x_{ij}(c_{ij} + VC_{ij} - lg_i - lg_j) + \sum_i \sum_j y_{ij}(lg_{ij} - lg_i - lg_j) +$$
$$\sum_i \sum_j \sum_k x_{ijk}(c_{ijk} + VC_{ijk} - lg_i - lg_j - lg_k) +$$
$$x_{1234}(c_{1234} + VC_{1234} - lg_1 - lg_2 - lg_3 - lg_4) + y_{1234}(lg_{1234} - lg_1 - lg_2 - lg_3 - lg_4)$$

$(i, j, k, l = 1, 2, 3, 4)$

c_{ijkl} = Cost of an extension to the national grid between groups i, j, k, l, with the minimum cost of interconnection for local grid lines.

VC_{ijkl} = Present value of cost of generation to meet the electricity needs for the group, and of O&M.

lg_{ijkl} = Present value of cost of microgrid to meet the electricity needs for the group, and costs of O&M, with the minimum cost of interconnection for local grid lines, and turbine located on the windiest place.

subject to:

$$x_1 + x_2 + x_{12} + y_{12} \leq 1 \qquad (1.1)$$

$$x_1 + x_3 + x_{13} + y_{13} \leq 1 \qquad (1.2)$$

$$x_1 + x_4 + x_{14} + y_{14} \leq 1 \qquad (1.3)$$

$$x_2 + x_3 + x_{23} + y_{23} \leq 1 \qquad (1.4)$$

$$x_2 + x_4 + x_{24} + y_{24} \leq 1 \qquad (1.5)$$

$$x_3 + x_4 + x_{34} + y_{34} \leq 1 \qquad (1.6)$$

$$x_1 + x_2 + x_3 + x_{123} + y_{123} \leq 1 \qquad (1.7)$$

$$x_1 + x_2 + x_4 + x_{124} + y_{124} \leq 1 \qquad (1.8)$$

$$x_2 + x_3 + x_4 + x_{234} + y_{234} \leq 1 \qquad (1.9)$$

$$x_1 + x_3 + x_4 + x_{134} + y_{134} \leq 1 \qquad (1.10)$$

$$x_1 + x_2 + x_3 + x_4 + x_{1234} + y_{1234} \leq 1 \qquad (1.11)$$

$$\sum x_i + \sum x_{ij} + \sum x_{ijk} + x_{1234} \leq 1 \qquad (2)$$

$$\sum y_i + \sum y_{ij} + \sum y_{ijk} + y_{1234} \leq 1 \qquad (3)$$

The objective is built such that, for example, if $x_i = 1$, then the cost of line to town *i* minus cost of local grid at *i* is considered, leaving the possibility that a local grid might be established for each town *j, k, l,* and ensuring the extension of the grid to *town i*. If $y_{jkl} = 1$, then the cost of microgrid in towns *j, k, l* together minus cost of local grid at *j, k, l* is also considered, leaving only the cost of a wind turbine servicing all three towns *j, k, l*.

Constraints (1.1)- (1.11) match feasible cases of connected and unconnected towns. With (2) and (3) only one group of connected and unconnected towns is evaluated. The case where $\sum y_{ij} = 1, \sum y_{kl} = 1$ must be treated specially.

For each of the options is necessary to pre-calculate the different paths of interconnection. The path with the lowest cost of the interconnection between the towns in a group is chosen for the model. Similarly, towns are identified according to their wind resources, from best to worst, and the wind turbines are located in the richest locations.

An optimization problem is not necessary when the number of towns in a group is less than four, and it can be explored manually. The number of different combinations of mix of technologies can be counted by using $\sum_{k=0}^{n} \binom{n}{k}$, where k is the total number of connected towns in each alternative. For four towns, $n = 4$, there are 16 different combinations, $\binom{4}{0} + \binom{4}{1} + \binom{4}{2} + \binom{4}{3} + \binom{4}{4}$. All options, but x_{1234}, are renewable or partially renewable, that is, with one or more autonomous villages. Dijkstra's algorithm can be used to find the path with the least cost. The different system options and interconnections must be evaluated within every combination. For every assessment, the wind turbine will be installed in the town with the best wind resources, adding the energy consumption for the group involved.

As an example, in Table 6 the situation of a group of towns formed by Santa Anita Las Cruces, San Joaquín, San José Ilusión, and Santa Anita la Ceiba is shown; their location is depicted in Figure 23. Considering individual towns separately, only for Santa Anita las Cruces was a better option to develop a grid extension compared to building a microgrid project as a consequence of the short distance to the national distribution network.

Figure 23. Location of NECs evaluated as a group (circled in red)

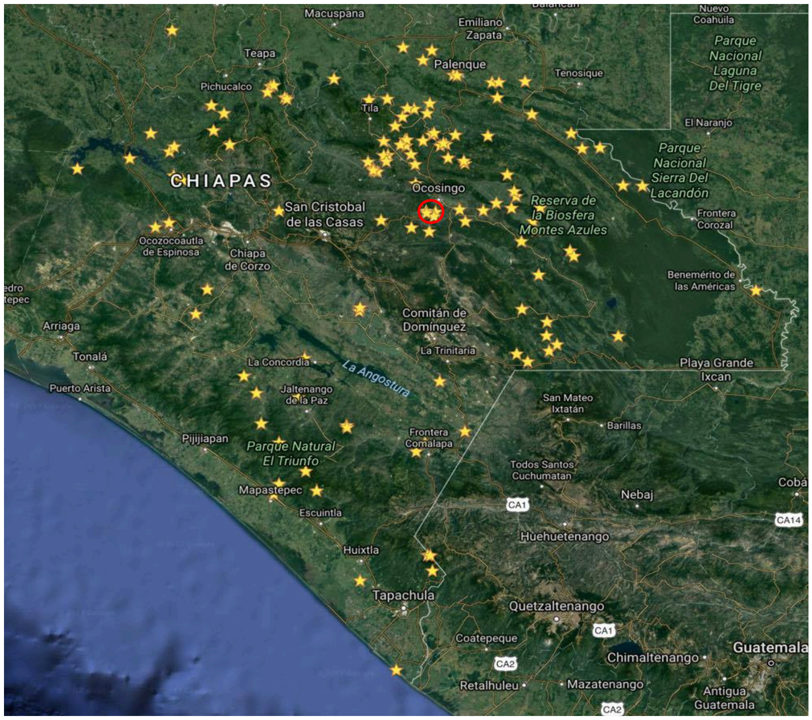
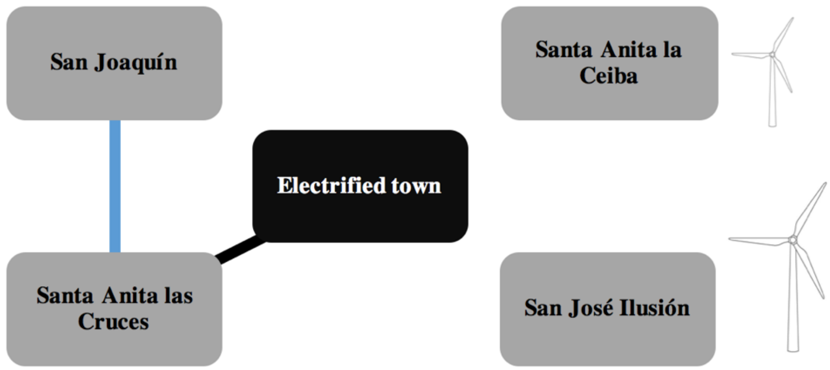


Table 6. Best solution for villages in isolated conditions

Town	Options for electrification
Santa Anita las Cruces	connection to the grid
San Joaquín	microgrid
San José Ilusión	microgrid
Santa Anita la Ceiba	microgrid

On their own, all of the communities benefit from a lower cost by placing a wind turbine in their location, except for the case of Santa Anita las Cruces, which should be still connected to the grid. Once the towns are assessed as a group, as seen in Figure 24, San Joaquín benefits from the interconnection to Santa Anita las Cruces and should be connected to the grid through Santa Anita las Cruces; a wind turbine is located in San José Ilusión and other in Santa Anita la Ceiba. Neither of them took advantage San José's good wind resources.

Figure 24. Change in solution for the electrification of NECs when evaluated as a group, shown in blue



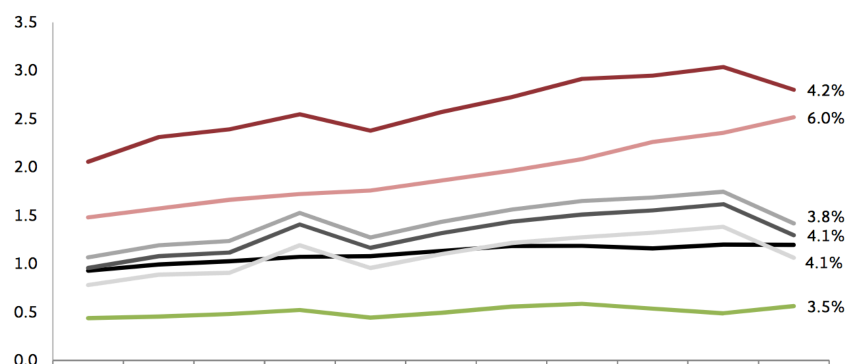
In the above-mentioned case, grouping reduces costs by allowing more interconnections between towns. Many other villages can benefit as well from neighbors' natural resources and interconnections; however, the actual specific benefits will depend on the geographic characteristics and available infrastructure between towns.

Chapter 11: Implementation and ranking system for electrification

Implementation of microgrids by CFE

CFE offers a subsidy in the electricity rate, which depends on the season, type of consumer and location (CRE, 2014). The subsidy benefits mainly domestic and agricultural uses (UTEXAS, 2013; SENER, Dec 2016). Typical projects increasing the grid in rural areas in Chiapas are completed with a social purpose, since they are subsidized. The rate without the subsidy was USDeq$.18 per kWh for domestic consumers in Chiapas during December (CFE, Dec 2016), from which CFE then can start recovering its costs. See average rates in Figure 25.

Figure 25. Average electricity rates for type of consumer in MXN per kWh



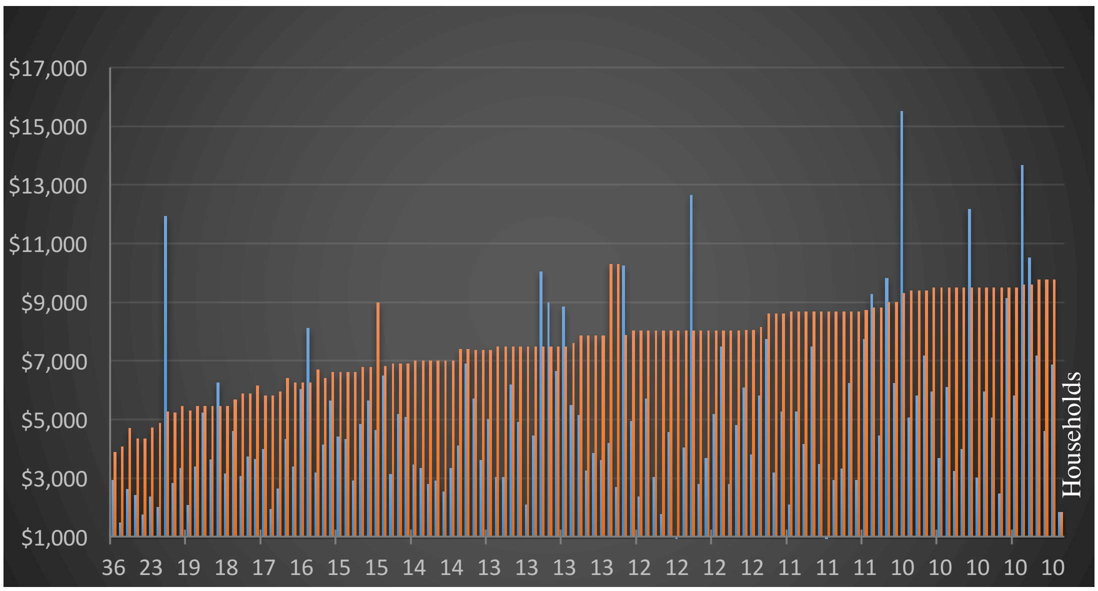
	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Comercial	2.1	2.3	2.4	2.5	2.4	2.6	2.7	2.9	2.9	3.0	2.8
Servicios	1.5	1.6	1.7	1.7	1.8	1.9	2.0	2.1	2.3	2.4	2.5
Empresa mediana	1.1	1.2	1.2	1.5	1.3	1.4	1.6	1.6	1.7	1.7	1.4
Residencial	0.9	1.0	1.0	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2
Gran industria	0.8	0.9	0.9	1.2	1.0	1.1	1.2	1.3	1.3	1.4	1.1
Agrícola	0.4	0.5	0.5	0.5	0.4	0.5	0.6	0.6	0.5	0.5	0.6
Industrial	1.0	1.1	1.1	1.4	1.2	1.3	1.4	1.5	1.6	1.6	1.3

Fuente: SIE, SENER.

Source: Secretaría de Energía, December 2016, Prospectiva del Sector, Eléctrico 2016-2030, http://www.gob.mx/cms/uploads/attachment/file/177626/Prospectiva_del_Sector_El_ctrico_2016-2030.pdf

If CFE intends to obtain revenue from microgrid-type of projects then it should increase its costs by sending employees to villages to obtain payment for the service. In case one employee visited every town with the bills, the cost would increase substantially. As seen in Figure 26, microgrids are even more expensive than typical projects once partial business travel expenses are considered. Since rural consumers pay a rate not adequate enough to recover the investment for a grid extension, it is even more insufficient to pay for a higher investment. Therefore, rural electrification is completed only as a non-profit endeavor, notwithstanding if it is completed using the grid or an autonomous system.

Figure 26. Cost of extension of the grid (blue) and cost of best solution with added expenses when a microgrid is installed (orange)



CFE can complete a project not only as a typical for-profit business, but also it can do it following socio-political reasons. CFE welcomes social impact and political benefits since it is a company owned by the government and whose CEO is appointed by the President of Mexico (Presidencia, 2016). If the objective of CFE is to provide electricity at a profit, then the solution is not to build any type of system in rural locations. Conversely, if the goal of the government is to provide an electric service for free, then CFE should focus on developing microgrids in most cases, so far as local communities agree. In such case, a feasible path for CFE would be to continue investments for significant, immediate, and cost-effective results.

CFE has two general options for the deployment and installation of microgrids: i) build independent systems for all villages, ii) install a wind energy system on the smallest villages due to the preference of consumers, and complete an extension of the grid for the largest towns. The option CFE chooses between the two will depend on the reception by locals. Rural communities might disagree with the construction and maintenance of microgrids. As previously stated, individuals might prefer waiting for the grid than accepting the installation of a microgrid. There is not an indication of the time limit rural communities are willing to wait or for which they are indifferent. However, in case customers do not have to pay for their electricity, they can have flexibility with respect of the technology that is offered to them and do not require a standard connection, which makes a microgrid a viable option for electrification. CFE could install microgrids in those communities where the cost to complete the electrification is lower for that system, without charging for the service.

Domestic rural electrification has social drivers, and consequently, it needs the full financial support of the local government or of non-governmental organizations. As formerly indicated, for Mexico, the WB funded the rural electrification program, and Mexican institutions only coordinated and completed the technical activities. Similar program in Costa Rica used low interest loans from USAID, while in Ireland, a proportion of the investment costs were covered by government grants. (Barnes, 2004). India targets to achieve deployment of micro and mini grid projects to meet the basic needs but also provide energy for services beyond lighting such as fan, mobile charging; productive and commercial requirement (MNRE, 2016).

Ranking system for the electrification of towns

Successful rural electrification programs have all developed their own system for ranking, not only for planning purposes but also to keep high levels of transparency (Barnes, 2004). Countries like Costa Rica, Thailand, and Ireland have developed a robust numerical classification system taking account a combination of factors (Barnes, 2004). Politicians in the developing world often interfere with the planning and running of rural electrification programs, connecting to the grid constituents first and preventing their disconnection when not paying the bills (Barnes, 2004).

In Mexico, an explicit order of electrification for remaining non-electrified villages has not been established yet. Based on numerous public statements, the only factor historically mentioned by the Mexican government as a decision variable to determine the order of electrification has been the number of inhabitants in a NEC; some of the other factors that could be taken into consideration are capital investment costs, total costs, distance from the present closest line, social needs, electrical requirements, number and density of consumers, unused installed power capacity, present and possible economic development, and socio-political aspects. In case the government considers more factors for future projects, a record with all the information for the variables involved is required. This analysis ads the cost of a microgrid as one variable that might be used to create a ranking system.

In previous sections, the costs of electrification for each household were determined for every system. The interaction of this new variable with the size of towns will be explored from Figures 27 to 29.

The cost of electrification with the grid for all towns are shown against the number of households in each town in Figure 27. As expected, the system benefits of economies of scale, although the distance causes a high variation between towns. The average cost of an extension of the grid is $4,971, and costs are scarcely dispersed. Towns with the largest number of houses have, in general, a lower cost, and have disproportionately more houses than smaller villages.

In Figure 28 the optimum cost of electrification for all towns and the number of houses are graphed as well. The number of houses electrified is also increased in the short term by starting with larger towns.

In case CFE continues with its current action plan, that is, electrifying the largest towns first, it will provide service for the largest number of people in the short term with a certain investment disregarding which technology it uses. The order of towns for electrification would substantially be changed by sorting them using costs instead of the size.

If optimum costs were used, towns with the largest population, based on CFE's current strategy, would have a substantial opportunity of receiving investment. Similarly, for those villages with the highest differential in costs (Figure 29) the optimum system will remain the same even if assumptions are modified.

Figure 27. Cost of extension of the grid and number of households for NECs. The polygon shows direction of future investments by CFE with current strategy

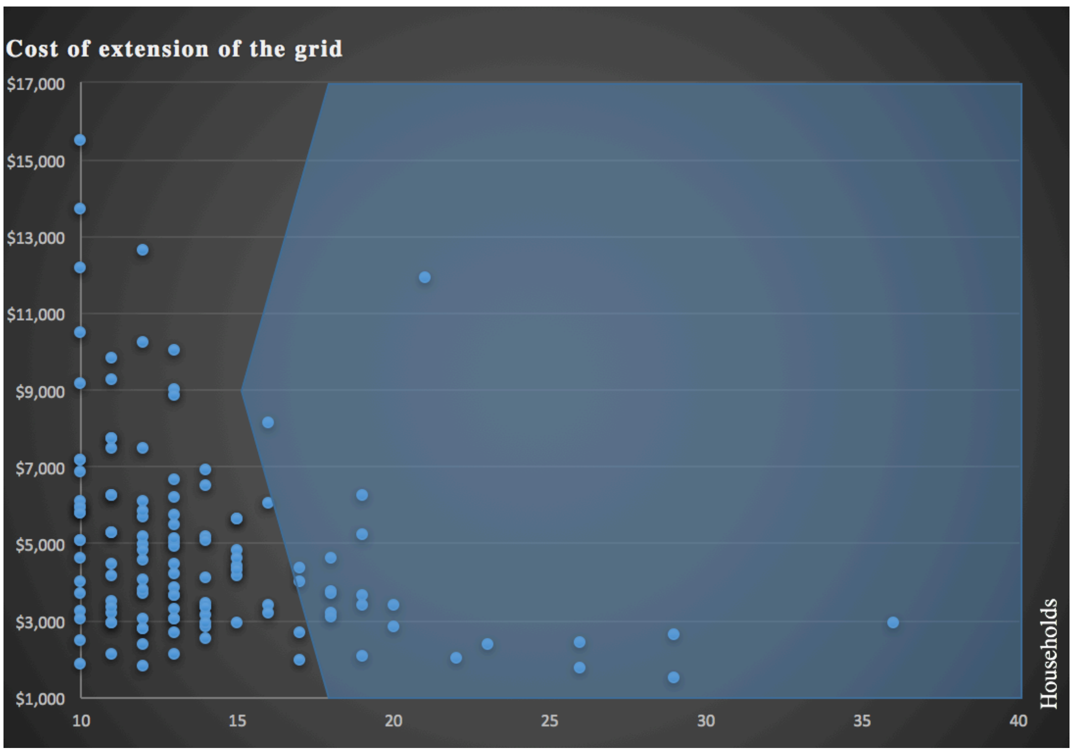


Figure 28. Cost of the best solution (mainly migrogrids) and number of households for NECs

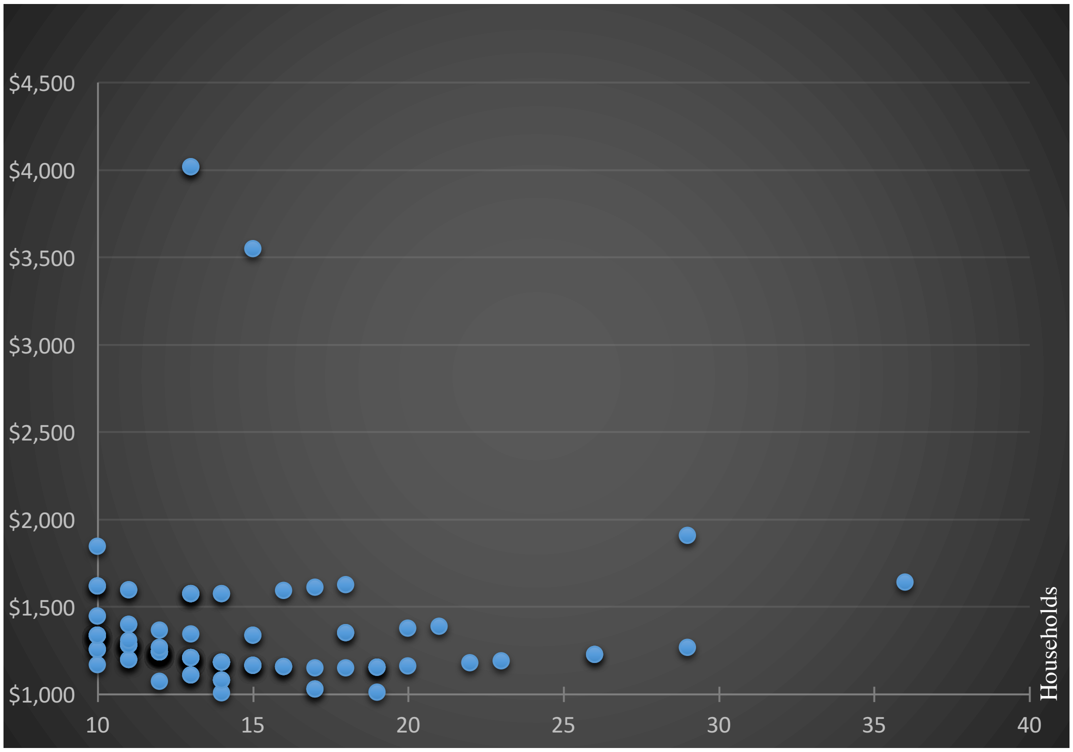
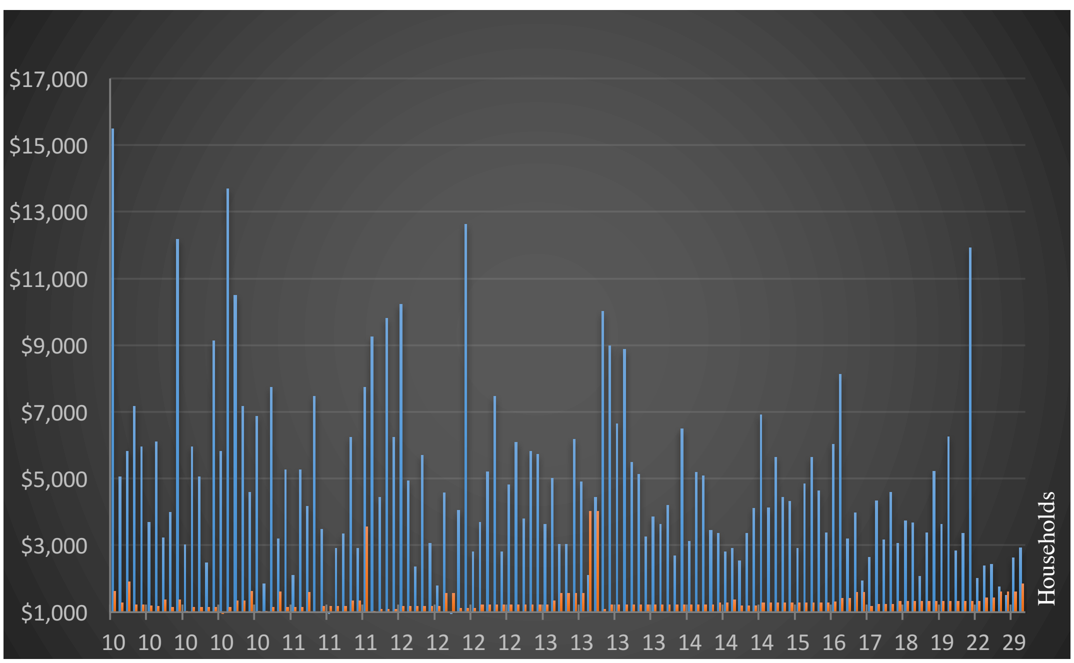


Figure 29. Cost of extension of the grid and cost of best solution



Government subsidy

In an effort to make rural electrification projects possible, the author explored the possibility of an agreement between a private wind developer and the government to rely not only on donations. In this format, the government would provide a subsidy to wind developers to make them generate electricity near a NEC instead of choosing the best possible location the company could otherwise find, as an option to increase local electrification. Companies would lose efficiency but gain a subsidy that should equal the revenue lost.

If A >B 0, then the government would sign an agreement with a wind energy company

A= (electricity bid price*efficient no. MWh) + cost to electrify the town

B= (electricity bid price*inefficient no. MWh in rural town) + subsidy

The wind density for Chiapas is similar to that where winning projects mentioned in chapter 9 were located, near the city of Merida, however, the mode of the wind speed for NECs in Chiapas is 5 m/s at a height of 30 meters, while for the winning projects is 7m/s. If companies generated electricity in Chiapas instead of investing in industrial wind farms near Merida, they would reduce the total annual generation, from 3,716 MWh to 1,354 MWh per 1MW of installed capacity. Wind companies sold electricity from wind sources to CFE at the average closing bid price of USD$42.7 per MWh (CENACE, 2016), consequently, the lost revenue would be USD100,722 per 1MW of capacity per year. In this scenario, the government would offer a significant subsidy, since the minimum installed capacity for a project was 30MW. Therefore, a government subsidy created to attract investment specifically where NECs are located and provide them with electricity would be higher than investing in an autonomous microgrid. Therefore, a subsidy of this nature would not be appealing for the government.

Chapter 12: Conclusions

The intention of this analysis was to evaluate whether the most significant obstacle to renewable energy development for rural electrification was the cost. This document tested the situation and provided a framework for the analysis. The investigation concluded that conventional electrification costs are higher than those of renewable energy projects, and that microgrids powered by wind turbines are feasible when compared to other options. Nevertheless, CFE will not be able to recover the investment.

The cost of a wind energy system was lower than a solar PV system, however the research and use of solar PV is more extensive. The reason might be related to the O&M. It is broadly recognized that solar panels might involve no moving parts, requires less monitoring, and maintenance. Additionally, problems have arisen in similar projects regarding O&M, particularly in Mexico. The WB reported several problems while implementing its program of electrification in Mexico caused by the different government institutions that included O&M issues: a) Training in maintenance was not adequate, b) roles and responsibilities of institutions involved were not adequately clarified by the coordinator, c) Lack of continuity of the members of the staff in charge of the project, d) Monitoring information was not provided on a timely basis causing delays. If the government truly wants to implement microgrids in NECs, it must create an implementation program to allow coordination and reduce costs (World Bank, 2016). It is important to have the full support of the local government and its employees to achieve an effective electrification.

For a successful application of electrification in remote locations, O&M is a factor important to evaluate. Since CFE employees are not required to work in risky areas, an alternative is to create an O&M program where individuals using the microgrid know how to operate it and give maintenance to the system.

So far, the analysis has followed the assumption that rural electrification must be completed, however, it might be the case that investment is not even made in the first place. According to Barnes (2004) rural electrification only makes sense in areas where there is already a substantial demand for services that use electricity, such as lighting, television and radio, kitchen appliances and motive power. It might be the case that local population cannot afford electric devices, but it is also possible that rural inhabitants do not have the option to acquire them since they do not have access to electricity at all.

Main non-financial variables were modified to see changes in the results: distance to the grid, cost of fuel, wind speed, and population.

As distance to the nearest electrified town was taken as a proxy, the real distance to the national grid could be less than the one considered, reducing the expenditure for an extension of the grid. For example, if the distance of all towns to the grid were reduced by one kilometer, except for those that are already closer than 1 kilometer, then the participation of the grid in towns increases, but only to 3% in total, due to variable costs.

For CFE, the cost of fuel represents 80% of total generation cost. CFE is changing its plans to use natural gas instead of oil derivatives as fuel for electricity generation. The cost per MWh has been reduced from MXN$2,000 to MXN$480 for those locations in a short period; CFE intends to keep migrating the remaining 20% of its plants to combined cycle gas plants (CFE, Jan 2015). Therefore, the fuel cost will still decrease, nevertheless, there is no estimation of future actual investments and its effect in the cost of fuel for CFE. A further analysis must be completed with new information that allows more extensions of the grid to be feasible objective.

Wind speed was not a factor that at the end determined the definitive system. Microgrids with wind speeds as low as 3.5 m/s showed lower costs than grid connection, given the distance of the national grid.

A diagram to identify NECs in a given area was described in section 8, and included a minimum and a maximum of inhabitants as part of a filter to determine the specific towns that would be evaluated. A higher maximum of individuals, mentioned in section b.4 as 100 inhabitants, becomes relevant for the determination of a system once the electricity requirement per capita of the population increases substantially, due to the use of productive activities, or growth of services, such as schools, public lighting, among others. In average, costs would be similar for the microgrid and the grid extension in towns with 376 individuals. On the other hand, the results indicate that a lower minimum of individuals, mentioned in section b.4, would benefit microgrids, making them even more attractive.

This thesis only showed an overall theoretical appraisal of the villages; it was not within the scope of the study, for example, to make a detailed assessment of a basic engineering study, which might include the specifications and sizing of the main equipment, or the conditions of the existing grid. The only possible way to make an accurate assessment of the villages is by visiting them; this is particularly important since social benefits, economic and academic progress might be related to the presence of productive rural activities that could benefit from electrification.

The economic viability of the alternative systems studied depends on the relative values of these analysis, and a better understanding of autonomous systems is critical to determine its cost-effectiveness, reliability, and the future of distributed energy in Mexico. The lack of sound data on the installation, operation, maintenance and retirement of the alternative systems in specific sites of rural villages in Mexico demands important simplifications in the analytic approach; however, the results and the framework applied in this thesis can be used as input for the development of a general model.

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